

Combustion and Incineration Engineering

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Abstract Thermal processes (drying, pyrolysis, and combustion) provide powerful means to reduce the volume and sanitize municipal solid wastes (MSW) and the residual solids of wastewater treatment. Solids removed by wastewater treatment processes include screenings and grit, floating materials (scum), and the concentrated solids from primary and secondary clarifiers (sewage sludge). This chapter reviews the basic technology and analysis tools relating to thermal processes, and presents the application of these tools in the management of both municipal solid wastes and sewage sludge (biosolids).

Key Words Sewage sludge • municipal solid waste • biosolids • combustion • incineration • pyrolysis • drying • air pollution • emissions • municipal waste combustors • multiple hearth furnace • fluidized bed • mass burning • refuse derived fuel • rotary dryer • tray dryer • indirect dryer • direct dryer.

1. INTRODUCTION TO INCINERATION

Solving the problem of volume is often the key to successful solid waste and sludge management. The low bulk density of solid waste or sludge requires costly storage containers at the point of generation, greatly affects the cost and difficulty of collection and handling, and is the primary factor in setting the cost and scale of landfill and other ultimate disposal operations. Incineration is often an attractive processing step to reduce the volume of solid waste and sludge. Properly, incineration should not be considered as

an ultimate disposal method since it cannot function without a landfill or other means to receive its solid residues.

In addition to volume reduction, incineration also offers the potential advantages of detoxification of combustible toxins and sanitation of pathologically contaminated material (especially important for biosolids), reduction of environmental impact related to the leaching of organic material from raw refuse or biosolids landfills, and provision of an energy resource through the use of a boiler enclosure. Extension of the scope of “incineration” to include gasification reactors introduces a new product: a “synthesis gas” composed largely of carbon monoxide (CO) and hydrogen (H₂) that has use as a chemical feedstock or as a clean fuel usable in diesel, turbine or fuel cell energy conversion systems.

The disadvantages of incineration include high capital and operating cost relative to many other waste management options, operating problems owing to the sensitivity of the process to changes in the character of the waste, staffing problems made more critical in light of the complexity of the process, potential secondary environmental impacts such as air and noise pollution and discharge of highly polluted wastewater, adverse public reactions in many cases, and technical risk reflecting the complexity of incineration systems.

2. PROCESS ANALYSIS OF INCINERATION SYSTEMS

The designer or analyst of an incineration system faces a formidable challenge. Incineration processes are complex, involving the interplay of chemical reactions, fluid flow, and heat transfer in a nonisothermal, nonhomogeneous, reacting system. This already complex physicochemical process is made less tractable to rigorous analysis by the ever-changing nature of the waste and the irregular pattern of major and minor adjustments of key parameters owing to the action of the plant operators or automatic control instrumentation.

This pessimistic picture, however, should not lead the engineer to abandon theoretical analysis as a powerful tool in design and problem-solving tasks related to incineration. In this chapter and in other texts (1, 2), the interested student or practicing engineer is introduced to analytical tools that facilitate the understanding and insight to cope with this important sector of environmental engineering.

The analytical methods presented here draw heavily on the disciplines of chemical and mechanical engineering, beginning with a review of the fundamentals of process analysis (heat and material balances, chemical kinetics, and equilibrium). This is followed by several topics relating to the fundamental processes occurring in burning, gasifying, and pyrolyzing systems.

2.1. Stoichiometry

Stoichiometry is the discipline of tracking matter (particularly the elements), partitioned in accord with the laws of chemical combining weights and proportions, and energy (in all its forms) in either batch or continuous processes. Application of the laws of conservation of mass and energy, supplemented by consideration of chemical kinetic and equilibrium relationships, provides great insight into the behavior of incineration systems.

Table 10.1
Values of the universal gas constant R for ideal gases

Energy	Pressure (P)	Volume (V)	Mols (n)	Temperature (T)	Gas constant (R)
–	atm	m ³	kg mol	°K	0.08205 $\frac{\text{m}^3 \text{ atm}}{\text{kg mol } ^\circ\text{K}}$
–	kPa	m ³	kg mol	°K	8.3137 $\frac{\text{kPa m}^3}{\text{kg mol } ^\circ\text{K}}$
kcal	–	–	kg mol	°K	1.9872 $\frac{\text{kcal}}{\text{kg mol } ^\circ\text{K}}$
joules (abs)	–	–	g mol	°K	8.3144 $\frac{\text{joules}}{\text{g mol } ^\circ\text{K}}$
ft-lb	psia	ft ³	lb mol	°R	1545.0 $\frac{\text{ft lb}}{\text{lb mol } ^\circ\text{R}}$
BTU	–	–	lb mol	°R	1.9872 $\frac{\text{BTU}}{\text{lb mol } ^\circ\text{R}}$
–	atm	ft ³	lb mol	°R	0.7302 $\frac{\text{ft}^3 \text{ atm}}{\text{lb mol } ^\circ\text{R}}$

In the paragraphs below, it will be advantageous to use the kilogram mol (or kilogram atom)—the molecular (atomic) weight expressed in kilograms—as the unit quantity. The advantage arises because one molecular (atomic) weight (mol) of any compound (element) contains the same number of molecules (atoms) and, for gases, occupies approximately the same volume (at similar pressures and temperatures). The approximation holds exactly if the gases are “ideal,” an assumption acceptably accurate for gases at atmospheric pressure and elevated temperatures.

2.1.1. Gas Laws

The relationship between absolute pressure *P*, absolute temperature *T*, and volume *V* for ideal gases is given by

$$PV = nRT$$

(1)

where *n* is the number of mols of the gas and *R* is the universal gas constant (Table 10.1).

EXAMPLE 1

To generate carbon dioxide for process use, 3000 kg/d of a waste containing 80% carbon, 7% ash, and 13% moisture is to be burned. The combustion gases leave the furnace at 1000°C and pass through a gas cooler, exiting at 80°C. How many kilogram-mols and how many kilograms of CO₂ will be formed per day? How many cubic meters of CO₂ are produced per day at the furnace outlet and at the gas cooler outlet at 1.04 atm?

The number of mols of carbon (atomic weight = 12) in the waste is (3000)(0.80)(1/12) = 200. Noting that with complete combustion each mol of carbon yields 1 mol of CO₂, 200 mol/d of CO₂ are produced. The weight flow of CO₂ (molecular weight = 44) is 200(44) = 8800 kg/d. From *PV* = *nRT*,

$$V = \frac{nRT}{P} = \frac{200(0.08206)T}{1.04} = 15.78T$$

at 1000°C (1273 K), *V* = 20,090 m³; at 80°C (353 K), *V* = 5570 m³.

2.1.2. Material Balances

A material balance is a quantitative expression of the law of conservation of matter:

$$\text{Input} = \text{Output} + \text{Accumulation} \quad (2)$$

This expression is always true for elements flowing through combustion systems but is often not true for compounds participating in combustion reactions.

The basic data used in calculating material balances can include analyses of fuels, waste, gases in the system, etc. (e.g., see Appendix) and some rate data (usually feed rate). Coupled with these data are fundamental relationships that prescribe combining proportions in molecules (e.g., two atoms of oxygen to one of carbon in carbon dioxide) and those that indicate the course and heat effects of chemical reactions.

Balances on elements in the fuel or waste allow one to calculate the amount of air theoretically required to completely oxidize the carbon, hydrogen, sulfur, etc. (recognizing that a portion of the oxygen required may be supplied by the oxygen contained in the material being burned). This quantity of air (known as the *theoretical* or *stoichiometric* air requirement) is often insufficient in a practical combustor, and excess air (expressed as a percentage of the stoichiometric air quantity) is usually supplied. For example, an incinerator operating at 50% excess air denotes a combustion process to which 1.5 times the stoichiometric air requirement has been supplied.

EXAMPLE 2

We are burning a waste with the following composition: 75.0% carbon, 6.2% hydrogen, 2.4% sulfur, 2.1% oxygen, 0.5% nitrogen, and 1.6% ash. The waste is burned with 50% excess air. The combustion air is at 15.5°C and 70% relative humidity. Calculate the flue gas composition and the quantity of combustion air that is required. The sequence of computations is shown in Table 10.2.

Several elements of the analysis on Table 10.2 should be noted:

- *Line 1:* Carbon is assumed to burn completely to carbon dioxide. In practice, some carbon may be incompletely burned (forming carbon monoxide), and some may end up as unburned carbon char in solid residues or as part of the particulate matter, leaving in the effluent gas as soot or char fragments.
- *Line 2:* Available hydrogen in the waste (other than the hydrogen in bound moisture) increases the amount of combustion air, but does not appear in the Orsat analysis (lines 16 and 17). Available hydrogen is presumed to react with oxygen (in the waste or supplied with the combustion air) to form water except for the hydrogen that preferentially reacts with organic chlorine to form hydrogen chloride (HCl).
- *Line 3:* Sulfur in the waste as sulfide or organic sulfur increases the amount of combustion air required in burning to SO₂. Inorganic sulfates may leave as ash or be reduced to SO₂. If selective analysis is not used for SO₂ (line 17), it is usually reported out as carbon dioxide. A small fraction (1% to 3%) of the SO₂ may be further oxidized to SO₃.
- *Line 4:* Oxygen in the waste reduces the amount of required combustion air.
- *Line 12.* Moisture entering as the humidity in the combustion air can be seen to be small and is often neglected. However, checking this assumption is prudent; especially in hot, humid locales.

Although this problem considered only waste components of C, H, O, N, and S, the analyst should review waste composition thoroughly and consider the range of possible secondary reactions:

Table 10.2
Calculations for Example 2

Line Component	kg	Atoms or mols ^a	Combustion product	Theoretical mols of O ₂ required	Moles formed in stoichiometric combustion					
					CO ₂	H ₂ O	SO ₂	N ₂	O ₂	Total
1 Carbon, C	75.0	6.245	CO ₂	6.245	6.245	0.0	0.0	0.0	0.0	6.245
2 Hydrogen, H ₂	6.2	3.075	H ₂ O	1.538	0.0	3.075	0.0	0.0	0.0	3.075
3 Sulfur, S	2.4	0.075	SO ₂	0.075	0.0	0.0	0.075	0.0	0.0	0.075
4 Oxygen, O ₂	2.1	0.066	–	(0.066)	0.0	0.0	0.0	0.0	0.0	0.000
5 Nitrogen, N ₂	0.5	0.018	N ₂	0.0	0.0	0.0	0.0	0.018	0.0	0.018
6 Moisture, H ₂ O	12.2	0.678	H ₂ O	0.0	0.0	0.678	0.0	0.0	0.0	0.678
7 Ash	1.6	N/A	–	0.0	0.0	0.0	0.0	0.0	0.0	0.000
8 Total		100.0		7.792	6.245	3.753	0.075	0.018	0.0	10.091
9 Mols of nitrogen in stoichiometric air ^b (79/21) (7.792)								29.312		29.312
10 Mols of nitrogen in excess air (0.5) (79/21) (7.792)								14.656		14.656
11 Mols of oxygen in excess air (0.5) (7.792)									3.896	3.896
12 Mols moisture in combustion air ^c						0.713				0.713
13 Total mols in flue gas					6.245	4.466	0.075	43.985	3.896	58.695
14 Volume (mol) percent in wet flue gas					10.64	7.61	0.13	74.97	6.64	100.0
15 Orsat (dry) flue gas analysis, mols					6.245		0.075	43.985	3.896	54.201
16 a. With selective SO ₂ testing, volume percent					11.52	N/A	0.14	81.15	7.190	100.0
17 b. With alkaline CO ₂ testing only, volume percent					11.66	N/A	N/A	81.15	7.190	100.0

^a The symbol in the component column shows whether these are kg-mol or kg-atom.

^b Throughout this chapter, dry combustion air is assumed to contain 21.0% O₂ by volume and 79.0% N₂.

^c Calculated as follows: (0.008/18)[(29.377 + 14.688)(28) + (3.905)(32)] based on the basis of 0.008 kg water vapor per kg bone-dry air; found in standard psychrometric charts and tables.

- *Carbon monoxide*: Carbon monoxide (CO) is formed in appreciable quantities in grate-fired systems burning solid wastes that do not incorporate air jets over the fire to add oxygen and thoroughly mix the off-gases from the grate's gasification zone.
- *Chlorine*: Chlorine appearing in the waste as inorganic salts will, most likely, remain in the ash as the salt. Some chlorides may volatilize to some degree. Organic chlorine, however, bonds with hydrogen from the waste and forms HCl. Similar behavior is seen for organic fluorine compounds such as Teflon®.
- *Metals*: Metals usually burn to the oxide, although, in burning solid wastes, a large fraction of massive metal feed (e.g., tin cans, sheet steel, etc.) remains unoxidized.
- *Thermal decomposition*: Some compounds may decompose at combustor temperatures. Carbonates, for example, may dissociate to form an oxide and CO₂, and sulfides may "roast" to form the oxide and release SO₂.

In many instances, the analyst is called upon to evaluate an operating waste disposal system. In such studies, accurate data on the flue gas composition are readily obtainable and offer a low-cost means to characterize the operation and the feed waste.

One important combustor and combustion characteristic that can be immediately computed from the Orsat (dry gas) flue-gas analysis is the percentage of excess air where O₂, N₂, etc., are the volume percentages of the gases on a dry basis.

$$\text{Percentage excess air} = \frac{[O_2 - 0.5(CO + H_2)]}{0.266N_2 - O_2 + 0.5(CO + H_2)} \times 100 \quad (3)$$

EXAMPLE 3

The flue gas from a waste incinerator burning a low ash hydrocarbon waste believed to have little or no nitrogen or oxygen has an Orsat analysis (using alkaline CO₂ absorbent) of 11.6% CO₂, 7.2% O₂, and the rest nitrogen and inerts. From these data, calculate the weight ratio of hydrogen to carbon in the waste, the percent of carbon and hydrogen in the dry waste, the kilograms of dry air used per pound of dry waste, the percent of excess air used, and the mols of exhaust gas discharged from the unit per kilogram of dry waste burned. (Note that this example is derived from Example 2.)

Basis: 100 mol dry exhaust gas

Component	Mols	Mol O ₂
CO ₂ (+SO ₂)	11.6	11.6
O ₂	7.2	7.2
N ₂	81.2	—
Total	100.0	18.8

Considering all N₂ to have come from the combustion air, a total of $81.2 \times (21/79) = 21.6$ mol O₂ entered with the N₂. The difference, $21.6 - 18.8 = 2.8$ mol O₂ may be assumed to have been consumed in burning hydrogen.

H ₂ Burned: $2(2.8) = 5.6$ mol	11.2 kg
C Burned: $12(11.6)$ mol	+139.2 kg
Total	150.4 kg

- a. Weight ratio of hydrogen to carbon: $(11.2/139.2) = 0.08$.
- b. Percent (by weight) C in dry fuel: $(139.2/150.4)(100) = 92.55$.
- c. Kilogram of dry air per kilogram of dry waste.

First, calculate the weight of air resulting in 1 mol dry exhaust gas from a nitrogen balance:

$$\frac{1}{100} (81.2 \text{ mol } N_2) (1/0.79 \text{ mol } N_2/\text{mol air}) (29 \text{ kg air/mol}) = 29.81 \text{ kg air/mol dry exhaust gas}$$

then, $29.81(100/150)$ mol dry exhaust gas/kg waste = 19.87 kg dry air/kg dry waste

- d. Percent excess air:

The oxygen *necessary* for combustion is: $11.6 + 2.8 = 14.4$ mol

The oxygen *unnecessary* for combustion = 7.2 mol

The total oxygen = 21.6 mol

Note that the *necessary* oxygen increases and the *unnecessary* oxygen decreases if incompletely burned components (such as CO) are present.

The percent excess air (or oxygen) may be calculated as:

$$\frac{(100) (\text{unnecessary})}{\text{total} - \text{unnecessary}} = \frac{100 (7.2)}{21.6 - 7.2} = 50\% \quad (4a)$$

$$\frac{(100) (\text{unnecessary})}{\text{necessary}} = \frac{100 (7.2)}{21.6 - 7.2} = 50\% \quad (4b)$$

$$\frac{(100) (\text{total} - \text{necessary})}{\text{necessary}} = \frac{100 (21.6 - 14.4)}{14.4} = 50\% \quad (4c)$$

- e. Mols of exhaust gas per kilogram of dry waste:

Noting that 5.6 mol water vapor must be added to the dry gas flow,

$$(100 + 5.6)/150.4 = 0.702 \text{ mol/kg waste.}$$

Lessons learned by comparing of the results of Example 3 with the “true” situation from Example 2 are as follows:

- Waste analysis data are important in calculating combustion air requirements for design.
- Waste moisture data are necessary to determine total flue gas rates.
- Insight into the nature of the waste can be gained from stack gas analysis.

If data are available, all data—for both fuel and flue gas—should be used to cross-check for consistency.

2.1.3. Heat Balances

A heat balance is a quantitative expression of the law of conservation of energy. In waste incineration, five energy quantities are of prime interest:

- *Chemical energy*: the heat of chemical reaction, especially the heat of combustion
- *Latent heat*: the heat effect of changes in state, especially the heat of vaporization of moisture
- *Sensible heat*: the heat content (enthalpy) related to the temperature of materials
- *Useful heat*: the heat available for use, especially the sensible heat available to generate steam
- *Heat loss*: the heat lost through furnace walls by conduction, convection, and radiation

In analyzing incineration systems, the heat of combustion of the waste is perhaps the seminal variable defining the size, burning capacity, air supply, air pollution control system design, fan capacity and horsepower, energy recovery potential, and on and on. Ideally, laboratory determinations of the heat of combustion are available. Often, however, the analyst is left with a component analysis (*X% paper, Y% wood, etc.*) or, at best, an ultimate analysis. Component analysis can be used to develop the overall ultimate analysis of the mixed waste by combining appropriate proportions of the ultimate analysis of each component (1). One can then synthesize the mean heat of combustion using estimation formulas.

The three heating value estimation relationships that follow were developed to estimate the heat of combustion (ΔH_c) of the combustible fraction of industrial and municipal wastes (kcal/kg) on a moisture and ash-free (MAF) basis. One uses the weight percent of hydrogen (H), oxygen (O), sulfur (S), etc. on a dry, ash-free basis. Substitute the percent (not the decimal percent) value for each in the following equations:

Chang equation (3):

$$\Delta H_c = 8561.11 + 179.72 H - 63.89 S - 111.17 O - 90.00 Cl - 66.94 N \quad (5a)$$

Modified Dulong equation (4):

$$\Delta H_c = 78.31 C + 359.32 (H - O/8) + 22.12 S + 11.87 O + 5.78 N \quad (5b)$$

Boie equation:

$$\begin{aligned} \Delta H_c = & 83.22 C + 275.48 H - 25.8 O + 25.0 S + 15.0 N \\ & + 9.4 Cl + 18.5 F + 65.0 P + 12.2 Fe \end{aligned} \quad (5c)$$

The Chang equation, the modified Dulong equation, and the Boie equation have been tested against one another for the prediction of the heat of combustion of 150 pure organic compounds where laboratory data were available to test the accuracy of prediction. In this comparison (1), the average error relative to the laboratory value was as follows: for Chang, 1.48%; for Dulong, 5.54%; and for Boie, 11.38%. Chang's equation was clearly superior for this task. The Boie equation, however, was originally developed and is well regarded for estimation of the heat of combustion of mixed wastes (especially high cellulosic material) such as refuse or wood. The modified Dulong equation is generally best for fuel-like, high carbon/hydrogen materials such as coal, peat, or lignite.

In heat of combustion and sensible heat calculations, 15.6°C (60°F) is often used as a reference point for "zero energy." Most values of heat of combustion reported in the American and British incineration literature are the higher heating value (HHV), which includes the latent heat of vaporization of the water formed in combustion (10,520 kcal/kg-mol at 20°C). See the Appendix for HHV values for refuse and refuse components. The lower heating value (LHV) is often reported in the literature of mainland Europe and the Far East and does not include the latent heat. By international agreement, the joule has been selected as the preferred energy unit. One kcal is equivalent to 4190.02 joules.

The sensible heat content (Δh) at a temperature T may be calculated relative to the reference temperature T_0 by:

$$\Delta h = \int_{T_0}^T M c_p^{\circ} dT \text{ kcal/kg mol} \quad (6)$$

where $M c_p^{\circ}$ is the molar heat capacity ($\text{kcal kg-mol}^{-1} \text{ }^{\circ}\text{C}^{-1}$, which is numerically equal in units of $\text{Btu lb-mol}^{-1} \text{ }^{\circ}\text{F}^{-1}$). The calculation may be carried out using an empirical equation describing the functional relationship of $M c_p^{\circ}$ on temperature (1). Also, one may use a graphical presentation (Figure 10.1) of the average molal heat capacity ($M c_{p,\text{avg}}^{\circ}$)

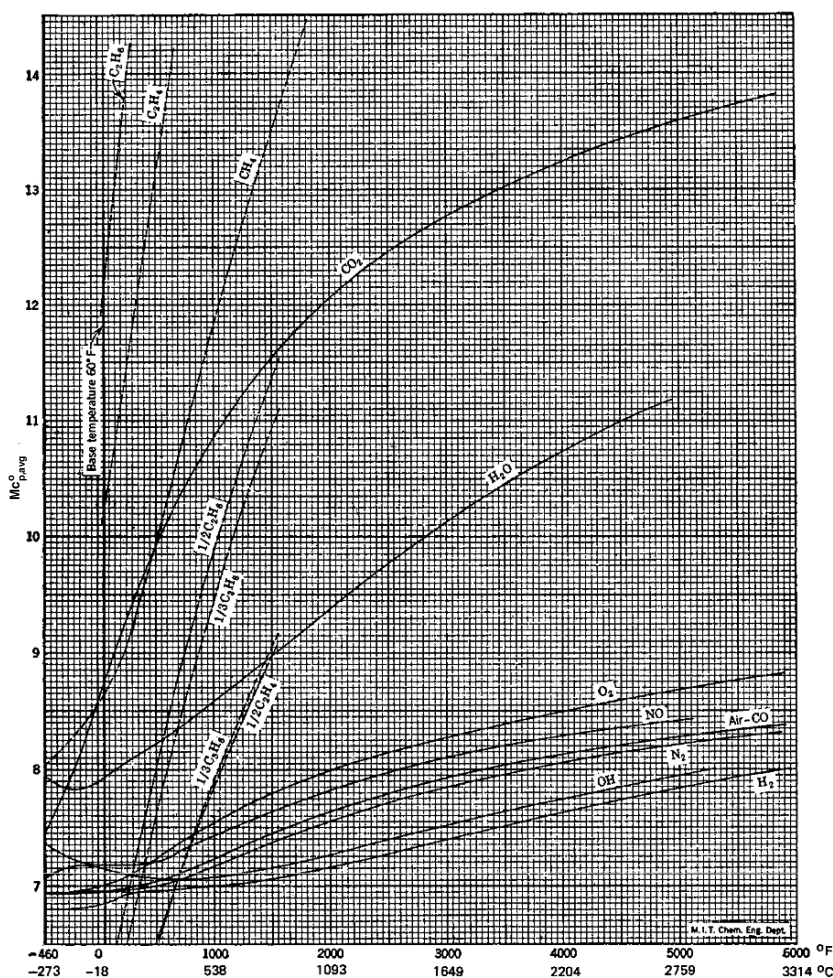


Fig. 10.1. Average molal heat capacity of fuel and combustion gases, ($M c_{p,\text{avg}}^{\circ}$), at zero pressure between 60°F (15.5°C) and abscissa temperatures. (Courtesy of Massachusetts Institute of Technology Chemical Engineering Department.)

between a reference temperature of 60°F (15.6°C) and the abscissa temperature. Thus:

$$\Delta h = (T - T_o)Mc_{p,ave}^o \quad (7)$$

EXAMPLE 4

If the 100 kg of waste described in Example 2 has a heat of combustion of 7500 kcal/kg (HHV) and the combustion air is preheated to 300°C, what is the temperature of the flue gases? How much steam can be generated if the gases are cooled to 180°C (about 350°F) in a boiler?

Assume 5% heat loss in the furnace and 5% in the boiler, and 570 kcal/kg enthalpy change from boiler feed water to product steam at 204°C. Basis: One hour of operation.

The total combustion air supplied to the system is $29.377 + 14.688 + 3(3.905) + 0.604 = 56.384$ mol (see Table 10.2). From Figure 10.1, the heat content of the preheated air at 300°C is:

$$(56.384)(7.08)(300 - 15.5) = 113,572 \text{ kcal}$$

Therefore, the total energy impact is

$$7500(100) + 113,572 = 863,572 \text{ kcal energy addition}$$

To find the exit temperature of the combustion chamber and the steaming rate, it is useful to construct a plot of the heat content of the gas stream as a function of temperature, computed as shown in Table 10.3 and presented in Figure 10.2.

The flows of thermal energy are then:

Energy flows	kcal	Temperature, °C
Energy into system = Heat of combustion	750,000	15.5
Air preheat	113,572	300
Total	863,572	1630*
Heat loss (5%) from combustion chamber	(43,180)	
Energy into boiler	820,392	1575
Heat loss (5%) from boiler	(41,020)	
Heat loss out stack	(117,615)	180
Net energy into steam	661,757	204

*The theoretical (adiabatic) flame temperature for this system (the temperature of the products of combustion assuming no heat loss).

For feedwater (at 100°C and 15.8 atm) changing to saturated steam at 15.8 atm, the enthalpy change is 567.9 kcal/kg, so that the resulting steaming rate for a burning rate of 1100 kg/h is:

$$\frac{661,757}{567.9} = 1165 \text{ kg/hour}$$

Table 10.3

Computation of heat content of flue gases from combustion of waste at 50% excess air

A.	Assumed temp., °C	180	500	1000	1500	2000
B.	A – 15.5°C	164.5	484.5	984.5	1484.5	1984.5
C.	$\text{Mc}_p^0 \text{N}_2^a$	6.93	7.16	7.48	7.74	8.10
D.	$\text{Mc}_p^0 \text{O}_2^a$	7.17	7.48	7.87	8.13	8.26
E.	$\text{Mc}_p^0 \text{H}_2\text{O}^a$	8.06	8.53	9.22	9.85	10.42
F.	$\text{Mc}_p^0 \text{CO}_2^a$	9.67	10.64	11.81	12.57	12.91
G.	Ash ^b	0.2	0.2	0.2	0.2	0.2
H.	Energy in N_2 43.985(B)(C)	50,109	152,250	324,480	507,925	699,850
I.	Energy in O_2 3.896(B)(D)	4594	14,230	30,565	47,430	65,350
J.	Energy in H_2O 4.466(B)(E)	5921	18,125	39,870	64,340	91,265
K.	Energy in CO_2 6.245(B)(F)	9937	32,540	73,210	116,910	162,210
L.	Energy in Ash 1.6(B)(G) + 85 ^c	53	290	450	610	770
M.	Latent Heat in H_2O 4.466 (10,595) ^d	47,320	47,320	47,320	47,320	47,320
N.	Total (H + I + J + K + L + M) ^e	117,880	264,689	514,600	781,800	1,057,501
O.	kcal/mol gas	2009	4512	8772	13,326	18,025

^a Source: Fig. 10.1 (kcal/kg mol °C).^b Specific heat (typical) of the ash (kcal/kg °C) for solid or liquid.^c The latent heat of fusion of the ash (85 kcal/kg) is added at temperatures greater than 800°C, the assumed ash fusion temperature.^d Latent heat of vaporization at 15.5°C of free water in waste and from combustion of hydrogen in waste (kcal/kg mol). Total heat content of gas stream (kcal).^e Total heat content of gas stream (kcal).

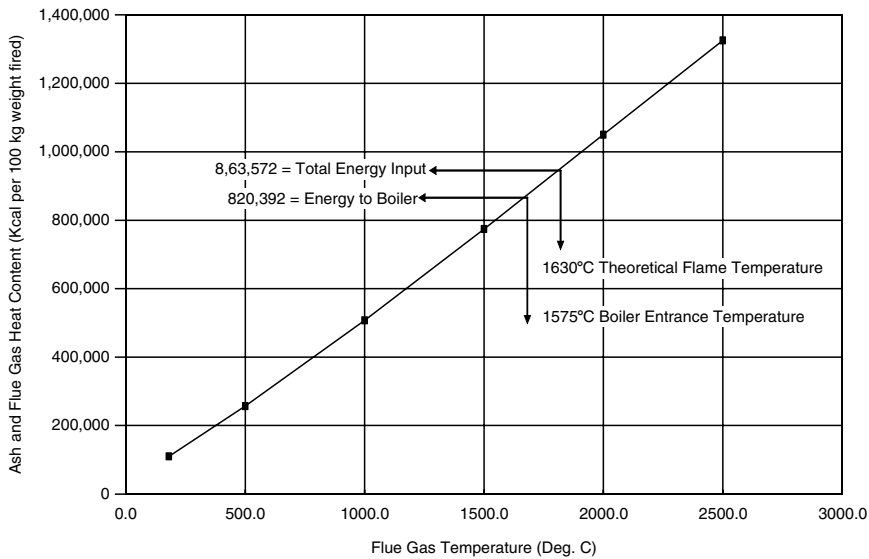


Fig. 10.2. Energy content of ash and flue gases as a function of flue gas temperature.

2.1.4. Equilibrium

No chemical reactions go to completion. Always, some fractions of the reactants remain in the reaction mass. For the gas phase reaction:



where the reactant and product concentrations are expressed as partial pressures P_A , P_B , ..., the equilibrium constant K_p , which is a function (only) of temperature, is given by

$$K_p = \frac{P_C^c P_D^d}{P_A^a P_B^b} \quad (9)$$

where the units of K_p depend on the stoichiometric coefficients a , b , c , and d . If $(c + d - a - b)$ is zero, K_p is dimensionless. If the total is nonzero, K_p will have the units of pressure raised to the appropriate integer or fractional power. Figures 10.3 and 10.3a show the temperature dependence of reactions of interest. Note that when solid carbon is a product or reactant, no partial pressure term for carbon is entered into the mathematical formulation.

EXAMPLE 5

At the furnace outlet temperature in Example 4 and at a total pressure of 1 atm, what is the emission rate of nitric oxide (NO) formed by the following reaction:



Component	Mols	Partial pressure (atm)
NO	x	$x/58.695$
N ₂	$44,083 - 0.5x$	$(44.083 - 0.5x)/58.695$
O ₂	$3905 - 0.5x$	$(3.905 - 0.5x)/58.695$
Total ^a	58.695	1.00

^a For this reaction, the total number of mols does not change.

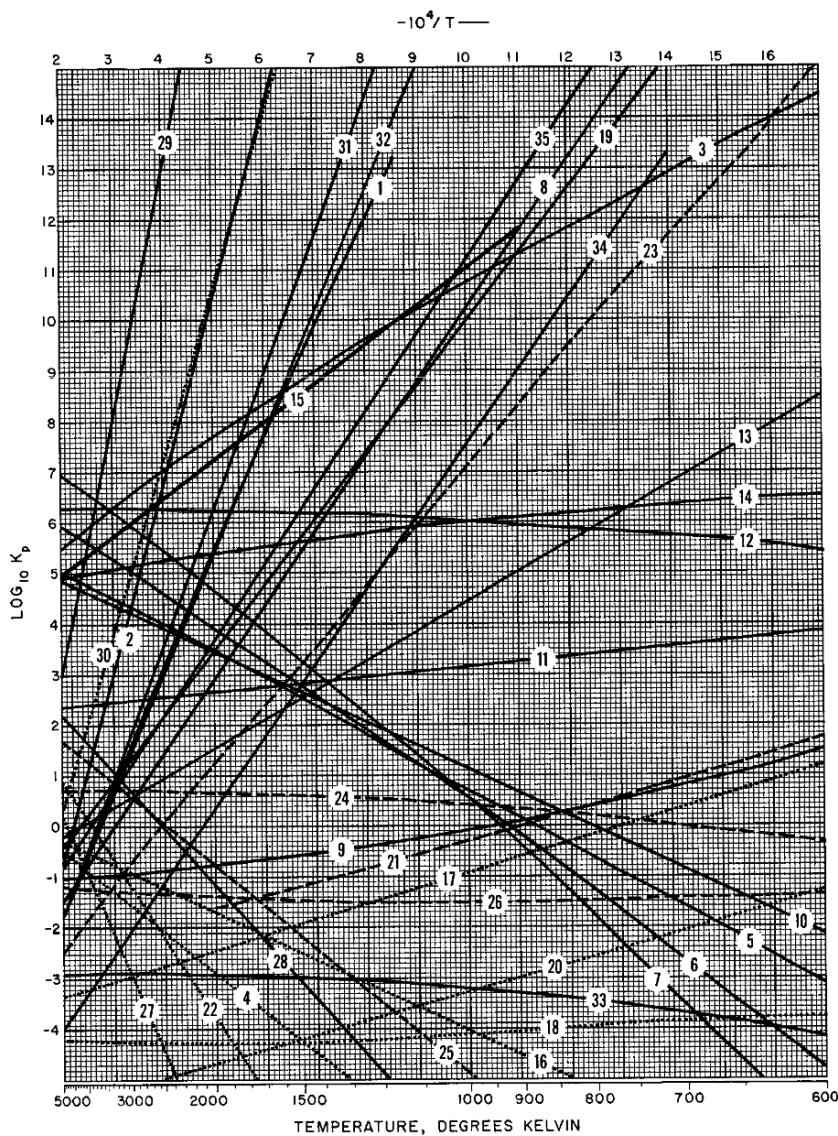
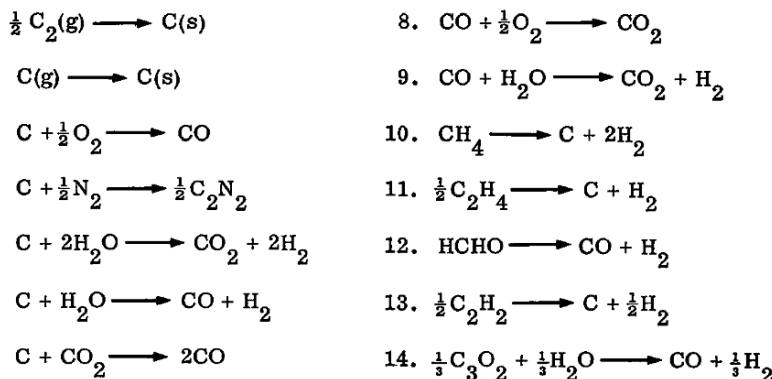
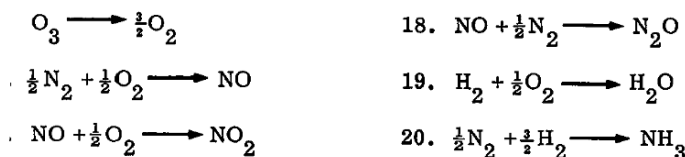


Fig. 10.3. Equilibrium constants of combustion reactions (partial pressure in atm). (Courtesy of Massachusetts Institute of Technology Chemical Engineering Department.)

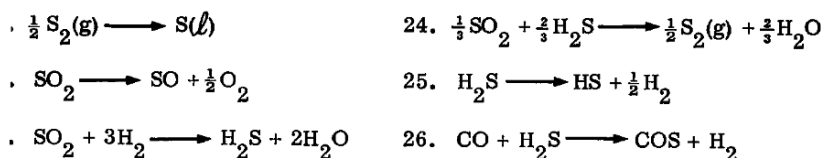
A. Carbon Reactions



C. Nitrogen and Oxygen Reactions



C. Sulfur Reactions



D. Radical Reactions

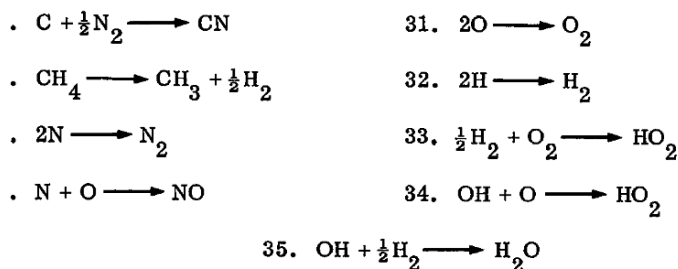


Fig. 10.3a. Reaction equilibria shown in Figure 10.3.

From Figure 10.3 at 1575°C, $\log K_p = 1.9$ ($K_p = 79.43$) where

$$K_p = \frac{P_{\text{O}_2}^{1/2} P_{\text{N}_2}^{1/2}}{P_{\text{NO}}}$$

At equilibrium, then:

$$(3.905 - 0.5x)^{1/2} (44.083 - 0.5x)^{1/2} = 79.43x$$

Solving this equation gives $x = 0.164$ mol NO at equilibrium, or 0.279 mol% or 2794 ppm. In practice, however, kinetic limitations usually result in NO concentrations substantially below those predicted by equilibrium alone. Note that the total “NO_x story” involves more than the “thermal NO_x” described by this equilibrium expression. See, therefore, other texts (1) that discuss the NO_x generation in more detail to include, for example, NO_x that derives from the nitrogen in the waste chemistry (“fuel nitrogen” NO_x).

2.1.5. Kinetics

All chemical reactions proceed at a finite rate depending on the concentration of the reactants, the static pressure (for reactions in the gas phase), and, importantly, the temperature. At combustion temperatures, reactions are usually very fast. Exceptions of importance are the oxidation reactions for carbon monoxide (CO), soot (carbon), and chlorinated hydrocarbons. Because of their importance as air pollutants, the reaction rate behavior (chemical kinetics) of CO and soot burning are discussed here.

2.1.5.1. KINETICS OF CARBON MONOXIDE OXIDATION

Carbon monoxide (CO) is an important air pollutant, a poisonous gas in high concentrations, and represents unreleased (wasted) fuel energy if found in stack gases. The rate expression by Hottel et al. (5) for the rate of change of the CO mol fraction (f_{CO}) with time is given by:

$$\frac{-df_{CO}}{dt} = 12 \times 10^{10} \exp - \left[\frac{16,000}{RT} \right] f_{O_2}^{0.3} f_{CO} f_{H_2O}^{0.5} \left[\frac{P}{RT} \right]^{1.8} \quad (11)$$

where f_{CO} , f_{O_2} , and f_{H_2O} are the mol fractions of CO, O₂, and water vapor, respectively, T is the absolute temperature (K), P is the absolute pressure (atm), t is the time in seconds, and R and R' are the gas constants expressed as $1.986 \text{ cal g mol}^{-1} \text{ K}^{-1}$ and $82.06 \text{ atm cm}^3 \text{ g mol}^{-1} \text{ K}^{-1}$, respectively.

The term $(-16,000/RT)$ is the heart of the kinetic expression, functionally providing a strong sensitivity to temperature through the exponentiation of the ratio of 16,000 (the Arrhenius activation energy) to the kinetic energy of the molecules as scaled by the absolute temperature.

It is instructive to note that the reaction rate is dependent on the water vapor concentration, a reflection of the key role of hydrogen (H) and hydroxyl (OH) free radicals in the complex series of fundamental combustion reactions that, summed together, result in the overall reaction written as $2CO + O_2 \rightarrow 2CO_2$. Indeed, bone-dry CO is very difficult to burn whereas even a trace of moisture is sufficient to assist in ignition and to facilitate rapid combustion.

2.1.5.2. KINETICS OF SOOT OXIDATION

When carbon-bearing wastes are burned, the existence of regions where the oxygen concentration falls to zero often results in the formation of soot (finely divided carbon). The high optical density of such black smoke can lead to violation of opacity regulations applying to stack discharges and creates system problems by fouling boiler tube surfaces, reducing the collection efficiency of electrostatic precipitators, etc.

Soot burnout is relatively slow in comparison to many other combustion reactions, owing in part to the slower pace of heterogeneous reactions and the possibility of diffusion limitations (viz., diffusion of oxygen to the surface of the soot particle).

For spherical particles, Field et al. (6) suggest that the rate of carbon consumption q ($\text{g cm}^{-2} \text{ s}^{-1}$) is related to the oxygen partial pressure in atmospheres (P_{O_2}) by:

$$q = \frac{P_{O_2}}{1/k_s + 1/k_d} \quad (12)$$

$$k_d = \frac{4.335 \times 10^{-6} T^{0.65}}{d} \quad (13)$$

$$k_s = 0.13 \exp \left[(-35,700/R) \left(\frac{1}{T} - \frac{1}{1600} \right) \right] \quad (14)$$

where k_s is the kinetic rate constant for the consumption reaction and k_d is the diffusional rate constant for particles of diameter d (cm) at a temperature T (K) and where R is the gas constant ($1.986 \text{ cal g-mol}^{-1} \text{ K}^{-1}$).

For a particle of initial diameter d_o and an assumed specific gravity of 2, the time t_b in seconds to completely burn out the soot particle is given by:

$$t_b = \frac{1}{P_{O_2}} \left[\frac{d_o}{0.13 \exp \left[\left(\frac{-35,700}{R} \right) \left(\frac{1}{T} - \frac{1}{1600} \right) \right]} + \frac{d_o^2}{8.67 \times 10^{-6} T^{0.75}} \right] \quad (15)$$

2.2. Thermal Decomposition (Pyrolysis)

The thermal decomposition or pyrolysis of carbonaceous solids in the absence of air or under limited air supply conditions occurs in most burning systems. Several solid-waste processing systems currently under advanced development exploit this process to effect gasification of refuse. Each produces a low heat-content gas stream containing volatilized water; a mixture of CO, hydrogen, and hydrocarbons; and a solid char, which often is burned completely in a specialized region of the "pyrolyzer."

Both physical and chemical changes occur in solids undergoing pyrolysis. The most important physical change is a softening effect, resulting in a plastic mass, followed by resolidification. Cellulosic materials increase in porosity and swell as volatiles are evolved.

As the cellulose pyrolysis begins (at about 200°C), complex, partially oxidized tars are evolved. As the temperature increases, these products further degrade, forming simpler, more hydrogen-rich gaseous compounds and solid carbon. The solid residue approaches graphitic carbon in chemical composition and physical structure.

The rate-controlling step in pyrolysis can be either the heat transfer rate into the solid or the chemical reaction rate. Below 500°C , the pyrolysis reactions appear rate-controlling for waste pieces less than 1 cm in size. Above 500°C , pyrolysis reactions are fast and both heat transfer and product diffusion are rate-limiting. For pieces larger than 5 cm, heat transfer probably dominates for all temperatures of practical interest.

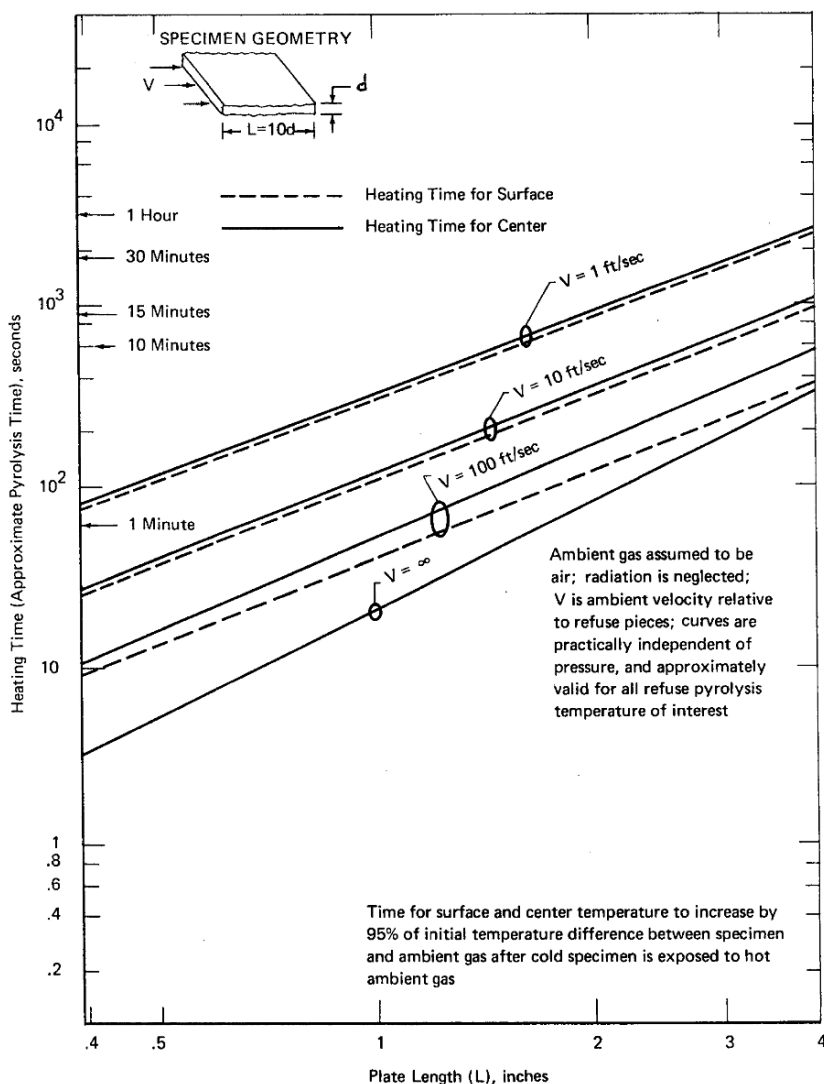


Fig. 10.4. Radiative and convective heating time for a thin plate.

2.2.1. Pyrolysis Time

The time required for pyrolysis of most wastes may be estimated by assuming that the rate is controlled by the rate of heating. Neglecting energy absorption or generation by reaction, Figures 10.4 and 10.5 facilitate estimation of the time for the center temperature of plates and spheres to rise by 95% of the initial temperature difference between specimen and surroundings. A thermal diffusivity of $3.6 \times 10^{-4} \text{ m}^2/\text{h}$ has been assumed, roughly equal to that of paper or wood (7). The heating time at infinite cross-flow velocity (V_∞) corresponds to radiant heating.

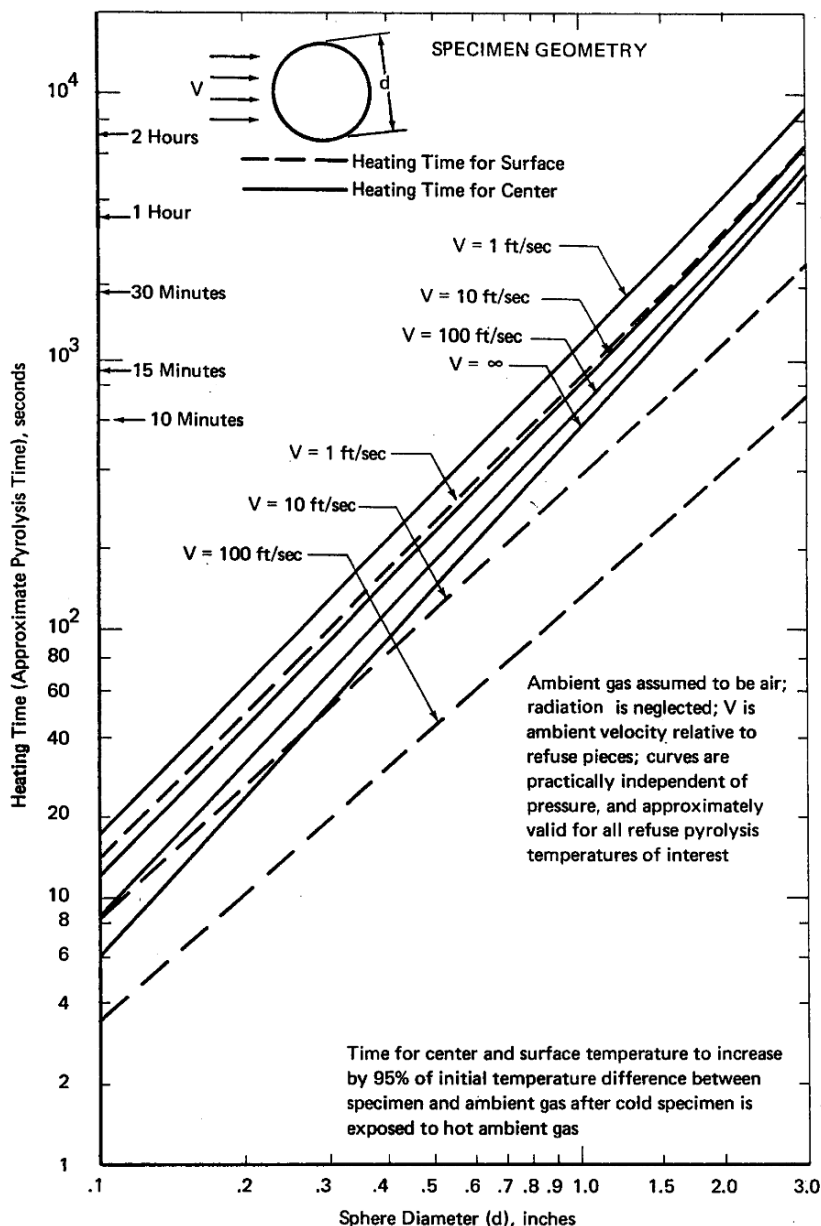


Fig. 10.5. Radiative and convective heating time for a sphere.

2.2.2. Pyrolysis Products

The pyrolysis products include ash and carbonaceous char in the solid phase; liquids (at room temperature), including H₂O, alcohols, aldehydes, and ketones (e.g., methanol, 2-methyl-1-propanol, 1-pentanol, 3-pentanol, 1,3-propanediol, and 1-hexanol), acetic and other acids; and gases, including CO, CO₂, H₂, and a variety of low molecular weight hydrocarbons.

The distribution between these products is known to be related to the heating rate and the ultimate temperature based on laboratory experiments with muffle furnaces. One

Table 10.4
Yields of pyrolysis products from different refuse components (weight % of refuse)^a

Component	Gas	Water	Other liquid	Char (ash-free)	Ash
Cord hardwood	17.30	31.93	20.80	29.54	0.43
Rubber	17.29	3.91	42.45	27.50	8.85
White pine sawdust	20.41	32.78	24.50	22.17	0.14
Balsam spruce	29.98	21.03	28.61	17.31	3.07
Hardwood leaf mixture	22.29	31.87	12.27	29.75	3.82
Newspaper I	25.82	33.92	10.15	28.68	1.43
II	29.30	31.36	10.80	27.11	1.43
Corrugated box paper	26.32	35.93	5.79	26.90	5.06
Brown paper	20.89	43.10	2.88	32.12	1.01
Magazine paper I	19.53	25.94	10.84	21.22	22.47
II	21.96	25.91	10.17	19.49	22.47
Lawn grass	26.15	24.73	11.46	31.47	6.19
Citrus fruit waste	31.21	29.99	17.50	18.12	3.18
Vegetable food waste	27.55	27.15	20.24	20.17	4.89
Mean values	24.25	23.50	22.67	24.72	11.30

^a Refuse was shredded, air-dried, and pyrolyzed in a retort at 815°C (8).

Table 10.5
Percent yields of pyrolysis products from refuse at different temperatures by weight of refuse combustibles

Temperature °C	Gases	Liquid (including water)	Char
480	12.33	61.08	24.71
650	18.64	59.18	21.80
815	23.69	59.67	17.24
925	24.36	58.70	17.67

From ref. (9).

suspects that another parameter affecting the degree of char gasification relates to the degree to which moisture, often evaporated and exhausted early in or prior to the test, is permitted to contact the char and thus engage in the water gas reaction:



Table 10.4 shows the yield of pyrolysis products from different substrates. Tables 10.5 through 10.8 show the effect of ultimate temperature and heating rate on product mix. Table 10.9 shows the significant differences in gas composition and heat content for differing feed materials, and Table 10.10 shows the distribution in the products of the elements comprising a mixed municipal refuse. The yield of liquid (including water) is approximately 50% to 60% of air-dried, ash-free refuse, decreasing with increasing ultimate pyrolysis temperature. The heat content of the liquid per pound of refuse decreases as the pyrolysis temperature increases.

For typical refuse, gas yield ranges from 15% to 35% of the air-dried feed, with the yield decreasing and then increasing as the ultimate pyrolysis temperature is raised from

Table 10.6
Effect of heating rate on yields of pyrolysis products and heating value of the newspaper

Time taken to heat to 815°C (min)	Yield of air-dried newspaper, wt%				Heating value of gas, kcal/kg of newspaper
	Gas	Water	Other liquid	Char (ash-free)	
1	36.35	24.08	19.14	19.10	1136
6	27.11	27.35	25.55	18.56	792
10	24.80	27.41	25.70	20.66	671
21	23.48	28.23	26.23	20.63	607
30	24.30	27.93	24.48	21.86	662
40	24.15	27.13	24.75	22.54	627
50	25.26	33.23	12.00	28.08	739
60	29.85	30.73	9.93	28.06	961
71	31.10	28.28	10.67	28.52	871

From ref. (8).

Table 10.7
Calorific value of pyrolysis gases obtained by pyrolyzing refuse at different temperatures

Temperature, °C	Gas yield per kg of refuse combustibles* m ³	Calorific value	
		Gas, kcal/m ³	Refuse combustibles, kcal/kg
480	0.118	2670	316
650	0.173	3346	581
815	0.226	3061	692
925	0.211	3124	661

From ref. (9).

* At 15°C, 1 atm.

480° to 925°C. In general, 1 kg of refuse combustibles yields 0.125 to 0.185 m³ of gas with a calorific value of about 3000 kcal/m³.

The solid char formed from refuse pyrolysis is an impure carbon, similar to coal in proximate analysis. Chars formed at 480° and 925°C are comparable to bituminous and anthracite, respectively. Char yields range from 17% to 32% of the air-dried, ash-free feed, decreasing with an increasing heating rate and ultimate temperature. The char heating value is around 6600 kcal/kg (air-dried) and decreases slowly as the ultimate pyrolysis temperature increases.

2.2.3. Decomposition Kinetics

Pyrolysis of cellulose appears to follow a two-step process. The first step involves breaking of the C-O-C bond to yield a mixture of sugar-like molecules, which subsequently degrade by further breaking of C-O-C bonding.

Studies by Kanury (10) using an X-ray technique to monitor density changes during the pyrolysis of wooden cylinders provides useful insight into pyrolysis kinetics.

Table 10.8
Composition of pyrolysis gases obtained by pyrolyzing refuse to different temperatures

Temperature, °C	Gas composition, volume %					
	H ₂	CH ₄	CO	CO ₂	C ₂ H ₄	C ₂ H ₈
480	5.56	12.43	33.50	44.77	0.45	3.03
650	16.58	15.91	30.49	31.78	2.18	3.06
815	28.55	13.73	34.12	20.59	2.24	0.77
925	32.48	10.45	35.25	18.31	2.43	1.07

From ref. (9).

Kanury’s data showed the pyrolysis reaction to follow:

$$\frac{d\rho}{dt} = -10^6(\rho - \rho_c) \exp\left(\frac{-19,000}{RT}\right) \tag{17}$$

where ρ is the instantaneous density (g/cm³) and the subscript c denotes char, t is time (min), R is the gas constant (1.987 cal/mol K), and T is the absolute temperature (K).

Kanury’s data showed little reaction up to 350°C, but rapid reaction above this point. Shivadev and Emmons (11), studying the pyrolysis of filter paper, show an ignition-like, rapid increase in reaction rate above 407 ± 15°C, in rough agreement with Kanury.

Scrap automobile tires were subjected to pyrolytic conditions using derivative thermogravimetric (DTG) and thermogravimetric analysis. In their investigations, Kim et al. (11) studied the pyrolysis kinetics and mechanisms for the compositional components of two different sections of scrap tire rubbers: sidewall and tread. They found that the breakdown of each of the compounds comprising the tires followed an irreversible, one-step decomposition mechanism.

The tires used in their experiments involved tread (comprised of two types of styrene-butadiene rubber) and sidewalls (a mixture of natural rubber and polybutadiene rubber). The resulting kinetic constants are shown in Table 10.11. The decomposition left a residue approximating 34% of the initial weight: approximately 28% the carbon black originally in the tire compounds and not lost in the pyrolysis event, plus about 6% ascribed to char residues of the thermal decomposition.

2.3. Mass Burning

In mass-burning incinerators, solid wastes are burned in a relatively thick bed. In an idealized conceptualization of the bed processes (after ignition down to the grate line):

- Complete combustion is occurring at and near the grate, consuming the oxygen in the air supplied under the grate to form CO₂ and H₂O.
- As the gases pass upward, CO₂ and H₂O react with char to form CO and H₂ in an endothermic reaction that, to a degree, is described by the water-gas shift equilibrium.
- Above this point, the only reaction that occurs is thermal pyrolysis of refuse in the essentially inert hot gases from below.

In the idealized mass-burning model described above, it was postulated that in thick beds the upper regions could behave as a true pyrolyzer. Evidence from coal and refuse

Table 10.9
Produced pyrolysis gas analysis

Waste material	Gas analysis (dry basis), volume percent							Heating value ^a	
	H ₂	CO ₂	CH ₄	CO	C ₂ H ₂	C ₂ H ₄	C ₂ H ₆	C ₃ H ₈	Btu/scf kcal/scm
MSW ^b	44.47	15.78	6.96	24.76	4.97	1.49	0.66	0.91	421 6750
Sawdust ^c	29.32	12.13	11.04	43.79	3.12	0.36	0.36	NM ^e	398 6380
Chicken manure	35.91	29.50	8.31	21.37	2.22	NM	0.61	NM	308 4940
Cow manure ^d	31.07	20.60	7.70	38.06	1.86	NM	0.31	NM	328 5260
Animal fat	11.57	27.63	18.12	14.72	25.05	NM	2.91	NM	683 10,950
Tire rubber	33.81	15.33	29.09	5.67	12.94	NM	3.17	NM	661 10,600
PVC plastic	41.02	19.06	14.51	20.76	4.02	0.21	0.43	NM	412 6600
Nylon	45.38	6.03	15.47	34.64	0.0	NM	0.0	NM	403 6460
Bituminous coal	46.88	11.68	16.63	21.71	2.08	NM	1.01	NM	435 6980
Sewage sludge (digested)	47.01	22.88	11.22	15.57	3.12	NM	0.21	NM	360 5770

^a scf, standard cubic feed (60°F, 1 atm); scm, standard cubic meter (15°C, 1 atm).

^b Average of five tests.

^c Average of three tests.

^d Average of two tests.

^e NM = Not measured.

From ref. (13).

Table 10.10
Dry-basis yields from pyrolysis of refuse in weight percent

	C, wt%	H, wt%	O, wt%	N, wt%	S, wt%	Ash, wt%	Total, wt%
Feed composition	30.85	3.84	22.32	(0.4)	(0.1)	42.49	100.00
CO	8.01	—	10.68				18.69
CO ₂	4.32	—	11.52				15.84
H	—	2.05					2.05
CH ₄	2.25	0.76					3.01
C ₂ H ₂	3.22	0.27					3.49
C ₂ H ₄	0.95	0.16	—		—		1.11
C ₂ H ₆	0.43	0.11	—				0.54
C ₃ H ₆	(0.52)	(0.09)	—				0.61
C ₃ H ₈	(0.35)	(0.08)	—				0.43
Liquids	3.45	(0.32)	(0.12)	(0.1)	—	—	3.99
Ash	—			—	—	42.49	42.49
Char	7.35			(0.3)	(0.1)	—	7.75
Pyrolysis product totals	30.85	3.84	22.32	(0.4)	(0.1)	42.49	100.00

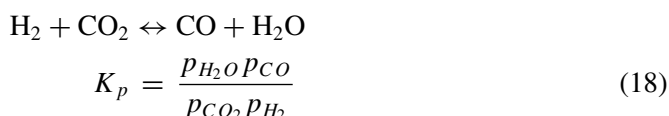
From ref. (14). Parentheses indicate estimated values.

Table 10.11
Kinematic parameters of scrap tire materials (27)

Material	ln A (min ⁻¹)	ΔE (kJ/g mol)
Processing oils in natural and polybutadiene rubber	7.84	48.0
Processing oils in styrene-butadiene rubber	7.56	43.3
Natural rubber	38.20	207.0
Butadiene rubber	34.08	215.0
Styrene-butadiene rubber	24.02	148.0

beds would tend either to discount the existence of the pyrolysis zone or, more probably, to suggest that this zone does not appear in beds of practical thickness (15, 16). Thus, the off-gas from a bed would be a mixture of gases from both burning and gasification zones.

Studies on the off-gas from refuse burning in a municipal incinerator (16) have confirmed the earlier data of Kaiser (17) and the hypothesis (7) that the off-gas composition is controlled by the water-gas shift equilibrium. This equilibrium describes the relative concentration of reactants in the following:



The importance of this equilibrium in mass burning is the incremental gasification potential given to the underfire air. In tests at Newton, Massachusetts (16), refuse and off-gas stoichiometry were studied. Average refuse was given the mol ratio formula: CH_{1.585}O_{0.625}(H₂O)_{0.655}. For this formula, and assuming that the water-gas shift

equilibrium holds, over 1.5 times as much refuse can be gasified as would be predicted for stoichiometric combustion to CO_2 and H_2O . Burning rate data showed rates 1.7 to 2.1 times that corresponding to stoichiometric combustion with the combustion air supplied beneath the refuse bed. Entrainment of air from above the refuse bed was assumed to occur to account for relative burning rates in excess of the 1.5 factor due to the water gas shift reaction. A second result coming from the water-gas shift reaction is that a definite and relatively large combustion-air requirement will necessarily be placed on the overfire volume. The air requirement for the CO , H_2 , distilled tars, and light hydrocarbons can indeed be as much as 30% to 40% of that expended in gasification, thus creating a need for effective overfire air injection and mixing.

2.4. Suspension Burning

In suspension burning, a particle of refuse is suddenly thrust into an environment of hot gases and intense radiative flux. The particle undergoes rapid drying and ignition while airborne, and proceeds to burn in an oxygen-rich atmosphere. Depending on the particle shape and weight, the velocity of the gas medium, and the geometry and dimensions of the combustion chamber, the particle may be partially or entirely burned while still suspended in the gas stream.

In general, the chemistry and heat transfer environment of the furnace and the details of the particle characteristics (moisture content, thermal and mass diffusivities, shape factors, etc.) are poorly defined, so that a rigorous analysis is difficult. Even for the somewhat simpler case of pulverized coal combustion, many simplifying assumptions are required to predict flame length, minimum air requirements, etc. (6).

For refuse, the second and third stages of the combustion process (heat-up of the dry solid and subsequent pyrolysis) may be analyzed using Figures 10.4 and 10.5.

2.5. Air Pollution from Incineration

Air pollutant emissions are central points of public concern and regulatory scrutiny for incinerators. Since the discovery of significant dioxin emissions from incinerator furnaces in the late 1970s, the fraction of incinerator plant capital cost related to compliance with air emission control has risen to more than 35% of the total investment. Often, resolution of public concern and reaching closure on the key permitting steps are the pacing and controlling events in the implementation of incineration facilities. Understanding the relationships between design and operating factors and air emissions and the relative effectiveness of alternative control technologies is critical.

Specifically, one must understand the relationship between emissions and the following:

- The specific chemical and physical characteristics of the wastes being burned
- The design features of the combustor
- The operating conditions in the combustor
- The control effected by the air pollution control device(s)

This knowledge allows a designer to set limits on the types or relative firing rate of the wastes burned and to configure the hardware design and operating strategy of the unit to ensure that air quality impacts remain within permit limits.

Air contaminants generated when burning fossil fuels or wastes have significance in three areas:

- Obtaining air emission permits from regulatory agencies
- Establishing the specifications for air pollution control systems
- Establishing the basic design, suggesting modifications to existing designs, or interpreting problems in emission minimization or control

Many air pollutants are emitted from combustion processes. Historically, the primary pollutant of concern was inorganic particulate matter. The total emission rate of particulate matter (total suspended particulate, TSP) is predominantly relatively inert “ash”—a mixture of benign compounds primarily composed of silicon, aluminum, calcium, iron, aluminum, and oxygen. However, this portion of combustor emissions can also include the “heavy metals” or “air toxics” (especially lead, mercury, chromium, cadmium, arsenic, nickel) and other elements that may have significant toxic, carcinogenic, and other health effects.

Also, the inorganic TSP includes an important portion of the small particle size material denoted as “PM_{2.5}.” PM_{2.5} is the respirable fraction under 2.5 μm in mass mean diameter that has been shown to have an important role in both the onset and aggravation of asthma and other respiratory diseases. Data on fine particulate matter show sulfates and nitrates to be the most abundant species in atmospheric aerosols with sulfates being the predominant contributor to PM_{2.5} (18). Inert particulate emissions are related to the fraction of ash in the feed and the fluid flow and other physical processes that can elutriate and convey the material from the combustion zone. A large fraction of the total PM_{2.5} found in the atmosphere is formed following discharge of the flue gases from gaseous SO_x and NO_x emissions that are PM_{2.5} precursors (secondary PM_{2.5}).

A second category of emission includes the combustible solids, liquids, and gases. A portion of these combustibles can be a fraction of the raw waste originally fed to the unit. Beyond this, there is a complex mixture of products of incomplete combustion (PICs) including carbonaceous soot and char; carbon monoxide; hydrocarbons and other volatile organic compounds (VOCs); and representatives of many classes of carbon-hydrogen-oxygen-nitrogen-halogen compounds such as benzene-soluble organic matter (BSO), polycyclic organic matter (POM) (e.g., benzo-(α)-pyrene), and a variety of polyhalogenated hydrocarbons (PHH), including the isomers and congeners comprising the families of polychlorinated and polybrominated dibenzo furans (PCDF, PBDF), p-dibenzo dioxins (PCDD, PBDD), and biphenyls (PCB, PBB). Net emissions of combustible pollutants such as the PICs arise partly from the waste chemistry (contributing “building blocks”), partly from failures in the combustion process (generating the PICs), and partly from successes in the combustion process (destroying a portion of the PICs).

Some of the organic or inorganic compounds emitted from incinerators exhibit or are suspected to exhibit significant adverse health effects. Some of the compounds react in the atmosphere (especially, under the influence of ultraviolet radiation) to generate ozone and a spectrum of eye-irritating oxygenated reaction products. With the great strides in sampling and analysis technology in recent years, the emission of these compounds can be quantified, regulated, and used as a basis for fines and penalties and, of vital importance, for continuation of permission to operate. In general, the net concentration of these pollutants in the atmosphere following normal dilution and dispersion following

emission from the stack is significantly below the threshold where significant health effects are probable.

There are several pollutants, emitted as both gases and solids, where the emission level is directly related to fuel chemistry. These include the sulfur oxides, the halogens and hydrogen halides (especially HCl), trace elements, and radioactive elements. Others, such as the nitrogen oxides, are emitted at rates related to both fuel chemistry and the combustion process.

A detailed analysis of the emission process and emission factor estimation and detailed discussion and quantification of the mechanisms by which pollutants arise and may be controlled are available elsewhere (1). This knowledge provides guidance from which the waste characteristics and the incinerator design features and operating conditions can be used to quantitatively estimate uncontrolled emission rates for many of the important pollutants. Such calculations and the physical principles that may underlie them also provide the designer and operator (both have a role in most cases) with tools to minimize the emission rates.

2.5.1. Mineral Particulate

The great majority of the emissions of mineral particulate are associated with the carryover of mineral matter introduced with the waste. The most important mechanism leading to these emissions is the entrainment of ash fragments by the flow of air and combustion products passing as underfire air through the burning refuse mass.

Important particulate characteristics include size, size distribution, shape, density, stickiness, corrosivity, reactivity, and toxicity. Of these, particle size distribution (PSD) has the most important impact on air pollution control and can be expressed as a particle count and as a mass distribution. Most commonly, the greatest mass is associated with the larger particles, but the greater number of particles, visual impact (opacity due to light scattering), surface area, and difficulty in capture is found with the smaller particles.

The Gaussian or “normal” distribution function is often used to describe many data populations. However, the log normal distribution function (1) is usually superior to characterize particles from industrial sources. In this case, a plot of the log of the particle size against frequency produces a straight line on log-probability paper.

Undergrate air velocities typically range from $0.05 \text{ m}^3/\text{s}/\text{m}^2$ of grate area to $0.5 \text{ m}^3/\text{s}/\text{m}^2$. An analysis of the entrainment process (1, 7) suggests that this range of velocities would entrain particles ranging in maximum diameter from 70 to 400 μm at a mean temperature of the entraining fluid of about 1100°C. The importance of the underfire air entrainment mechanism on emissions is supported by the observed range of particle sizes of fly ash, the increases in particulate emission with undergrate air velocity, and the similarity in the chemical analyses of fly ash and that of the refuse fine ash (1).

Eberhardt and Mayer (19) and Nowak (20) report that 10% to 15% of the refuse ash can be expected to appear in the gases leaving the furnace. Data from the U.S. Public Health Service (PHS) on an experimental incinerator (21) showed emission rates from 8% to 22% of that in the refuse for underfire air rates comparable to those used in municipal incinerators.

The relationship between underfire air rates and emissions were correlated by the PHS as:

$$W = 4.35 v^{0.543} \quad (19)$$

where W is the emission factor (kg/ton of refuse burned) and v is the undergrate air flow ($\text{sm}^3\text{s}^{-1}\text{m}^{-2}$). Data on three municipal incinerators obtained by Walker and Schmitz (22) showed general agreement with Equation 19 but scattered $\pm 20\%$.

Small effects on emission rate are also shown by incinerator size (emissions increasing as size increases, perhaps owing to the natural convection effects on the velocity field in the furnace); burning rate relative to design capacity [Rehm (23) noted a 30% reduction in furnace emissions with a 25% reduction in throughput]; grate type (lower emission being associated with grates where sizable air openings pass a large fraction of the fine ash out of the flow as siftings); and several still lesser effects (1).

2.5.2. Combustible Solids, Liquids, and Gases

By definition, the appearance of combustible pollutants (soot, char, CO, and a spectrum of hydrocarbons) in the effluent of a combustion system reflects an inadequacy in combustion efficiency. This indicates any or all of the following:

- Inadequate residence time to complete combustion
- Inadequate temperature levels to speed combustion reactions to completion
- Inadequate oxygen concentrations in intimate conjunction with the combustibles to allow oxidation to proceed to completion, often indicating incomplete mixing rather than an oxygen deficiency in the overall flow.

Complete combustion is a basic objective of almost all combustion systems. In most real systems, however, the full attainment of this goal is either impossible or impractical. Thus, some unburned combustible will always be present in the effluent gases. In the 1970s and afterward, one saw several forces in the environmental area that focused attention on incompletely burned species:

- Air pollution aspects of the basic pollutants (particulate, NO_x , SO_2 and CO) were well understood. Air quality criteria (denoting the relationship between the long-term average concentration of the pollutant and human health effects) were set. The academic and the regulatory community were seeking new areas of endeavor.
- Analytical equipment and sampling/analysis techniques were rapidly evolving. It was now possible to identify and quantify the specific chemistry of complex organic species in flue gases. The combustor's "chemistry set" produces a spectrum of products: a broad range of polynuclear, oxygenated, halogenated, and otherwise medically significant species. The concentrations were small but the classes of compounds (POMs, halogenated organic compounds etc.) were provocative.
- Methodologies were emerging to evaluate the health risk of exposure to subacute levels of pollutants. Further, the public had seized on health risk as a new scale against which to evaluate projects.

These factors fostered increasing awareness and concern by regulatory authorities throughout the world over the health implications of combustible emissions. This concern emphasized the importance of careful design and operations to minimize both generation and survival of these pollutants.

The incomplete combustion of carbon-containing fuels or waste materials forms a spectrum of chemical species. Due to the refractive index and color of carbon particles and to the typically small particle size, the simplest product of incomplete combustion (carbon itself) contributes importantly to the opacity of the effluent. Small particles have a greater light scattering power for a given mass loading than coarse particles. Carbonaceous soot can be amorphous in character but is more often graphitic. This is unfortunate since graphitic carbon is more difficult to oxidize than the amorphous material.

Carbon-hydrogen compounds comprise the second class of combustible pollutants. These compounds include methane, ethane, acetylene, and other simple straight and branch-chained aliphatic compounds as well as complex saturated and unsaturated ring compounds. The health significance of these pollutants varies greatly. The subclass of complex aromatic compounds (POMs) includes compounds such as the carcinogenic benz- α -pyrene.

Carbon-hydrogen-oxygen compounds comprise the third class of pollutants. These pollutants range from simple compounds such as CO and formaldehyde to complex organic acids, esters, alcohols, ethers, aldehydes, ketones, and so forth. These compounds are often associated with odorous emissions and show very low minimum detection concentration limits. In particular, aldehydes that are formed as PICs are often major contributors to the burnt smell.

The fourth class of pollutants includes the carbon-hydrogen-nitrogen compounds. These include the PICs formed from combustion of amines, N-ring compounds, many proteins, and other chemical species. Some also incorporate oxygen in the molecule. These compounds are especially significant due to their participation in the formation of fuel nitrogen NO_x and their contribution to odor.

Carbon-hydrogen-oxygen-halogen compounds are the fifth class of pollutants. These pollutants include chlorinated solvents, fluorinated and chlorinated polymers, and many other environmentally significant PIC-derived chemical compounds. Importantly, this class includes the several congeners and isomers of polychlorinated dibenzo-p-dioxin, dibenzo-furan, and biphenyl compounds. The chlorinated solvents and polymers contribute to the formation of the halogen acids (HF, HCl, HBr, and HI) that, under U.S. law, often triggers a requirement for acid gas control. Members of the polychlorinated dioxins, furans, and biphenyls are under intense scrutiny by the regulatory community and the general public worldwide. Carcinogenicity and other significant health effects are often associated with these materials.

The incompletely burned or PIC pollutants associated with almost every criterion of air quality include the following:

- Solid particulate or aerosols that contribute to atmospheric haze and solids fallout
- Photochemically reactive compounds that participate in the reactions leading to smog
- Compounds recognized as injurious to plants (e.g., ethylene) or animal life respiration (e.g., carbon monoxide), known to cause cancer in human beings (e.g., benz- α -pyrene), or known to promote adverse health effects in animals similar to that of pesticides (e.g., halogenated biphenyls).

Because of the health-related impact of these pollutants, their control assumes an importance out of proportion to the weight emitted.

The solution of the combustible pollutants problem is generally associated with the attainment of intense mixing in the hot regions of the furnace and provision of sufficient residence time for combustion reactions to be completed. The soot and CO kinetics discussed above allow estimation of the order of magnitude of time and temperature required after an adequate degree of mixedness is attained.

2.5.3. Acid Gases

Sulfur dioxide and hydrogen halides are emitted in proportion to the concentration of elemental sulfur, metal sulfides, organic sulfur-bearing compounds (mercaptans, sulfides, disulfides, etc.), and halogen-bearing organic compounds. In the incineration environment, oxidation of the sulfur or sulfur compounds and reactions of the halogens with hydrogen sources (e.g., $-\text{OH}$ or $-\text{OH}_2$ radicals) forms SO_2 and the appropriate halogen acid (HF , HCl , HBr , or HI). Estimation of their importance as pollutants, therefore, is to some extent dependent on the results of a comprehensive waste analysis for the area in question.

Sulfur oxides arise primarily from the oxidation of sulfur or sulfides, or from organic or inorganic sulfur-based acids. Owing to some absorption by alkaline fly ash, only about 70% of this sulfur will appear as SO_2 or SO_3 in the flue gases, by analogy with coal burning plants (24). About 97% of the sulfur appears as SO_2 and 3% as SO_3 .

Hydrogen chloride arises most importantly from the incineration of municipal refuse components such as polyvinyl chloride (PVC, 59% chlorine) and polyvinylidene chloride (Saran, 73.2% chlorine). Conversion of the organically derived chlorine to hydrogen chloride in the furnace gases is almost quantitative. PVC has been posed as one of the primary sources of the halogen content of the polychlorinated dioxin compounds found in incinerator effluent. However, dioxin emission data from incinerators fired with known quantities of PVC showed no correlation between the HCl concentration in the flue gases and the dioxin emissions (25, 26).

2.5.4. Nitrogen Oxides

Nitrogen oxides (NO , NO_2) are formed in all air-oxidized combustion reactions, although nitrogenous fuels produce significantly higher concentrations than fuels barren of nitrogen. The fixation of nitrogen with oxygen occurs by the following overall chain reaction mechanism after Zeldovitch (27).

Equilibrium considerations lead to the following relationship for the overall reaction:



$$K_p = \frac{(\text{NO})^2}{(\text{N}_2)(\text{O}_2)} = -21.9 \exp \left(\frac{-43,400}{RT} \right) \quad (21)$$

The rate of formation of NO is significant only at temperatures in excess of 1000°C due to kinetic limitations, and doubles for every 40°C increase in flame temperature. Thus, NO_x emissions are encouraged by high flame temperatures (e.g., by air preheat) and high excess air. NO_x can be reduced by the following:

- Water or steam injection or flue gas recirculation (to lower flame temperature)
- Operation at low excess air (to reduce oxygen concentrations)

- Staged combustion where the fuel is partially burned, heat is withdrawn through boiler surfaces, and then the rest of the required air for combustion is added (the overall effect is to lower the peak temperatures attained after the combustion gases contain a net excess of oxygen)
- Selection of burner designs (“low-NO_x burners”) that reduce the combustion intensity (volumetric burning rate), produce relatively long diffusion flames, or produce either two-stage combustion or low-temperature gas recirculation

A kinetic evaluation by Soete, reported by Bowman (28), can be solved iteratively to estimate the decimal fraction Y of fuel nitrogen N_f converted to NO. For $[N_f]_o$ equal to the NO concentration for 100% conversion of N_f to NO and $[O_2]$, the oxygen concentration (gmol/cm³) and temperature T in degrees K, the following can be developed as a basis to estimate fuel-nitrogen related NO_x generation:

$$Y = \left[\frac{2}{1/Y - \{[2.5 \times 10^3 [N_f]_o] / [T \exp(-3,150/T) [O_2]]\}} \right] - 1 \quad (22)$$

Liquid injection vortex type incinerators were studied by Kiang (29), who developed a *dimensional* empirical relationship between the percent of fuel nitrogen converted and several key design and operational parameters:

$$\log_e [Y] = 2.9 - 1.027S - 0.4665 \log_e [\text{percent } O_2] - \frac{158.2452}{T} \quad (23)$$

where

Y is the percent of fuel nitrogen converted to NO (as a percent)

S is the mean residence time (seconds)

Percent O₂ is the dry percent oxygen (as a percent)

T is the temperature (degrees F)

Kiang found that the formation of NO was not related to the specific chemical form in which the nitrogen is found in the fuel (amine, cyanide, amide, nitroso group, etc.) nor to the partial pressure of water vapor in the incinerator flue gases.

Based on work by the PHS on fossil fuels (30), an estimate of the nitrogen oxides emission (expressed as NO₂) for refuse combustion as related to the heat release rate (kcal/hour) is given by:

$$\text{kg NO}_x/\text{hr} = [(\text{kcal}/\text{hour})/2.26 \times 10^6]^{1.18} \quad (23)$$

2.5.5. Air Toxics

The term *air toxics* has been applied to a spectrum of organic and inorganic compounds found in stack emissions. The U.S. Environmental Protection Agency (US EPA) defines air toxics as pollutants known or suspected of causing serious health concerns such as cancer or birth defects. The US EPA's list of air toxics as of the year 2000 is shown in Table 10.12.

The health effects triggering inclusion in the air toxics list are summarized in Table 10.13. In many (if not most) cases, the concentration of these compounds in the stack gases is small; they are micropollutants. Thus, after dispersion and dilution of the stack gases by the atmosphere, the resulting average ambient air concentrations and

Table 10.12
Air toxics

Acetaldehyde	Ethylene oxide
Acrolein	Formaldehyde
Acrylonitrile	Hexachlorobenzene
Arsenic compounds	Hydrazine
Benzene	Lead compounds
Beryllium compounds	Manganese compounds
1,3-butadiene	Mercury compounds
Cadmium compounds	Methylene chloride
Carbon tetrachloride	Nickel compounds
Chloroform	Polychlorinated biphenyls (PCBs)
Chromium compounds	Polycyclic organic matter
Coke oven emissions	Quinoline
Dioxin/furans*	1,1,2,2-tetrachloroethane
Ethylene dibromide	Perchloroethylene
Propylene dichloride	Trichloroethylene
1,3-dichloropropene	Vinyl chloride
Ethylene dichloride	Diesel particulate matter*

* Health effect results not yet available.

Source: US EPA (2000).

Table 10.13
Health effect classifications

Health effect class	Characteristic impact
Toxic	Kills cells or the organism by poisonous nature; often, a threshold dose (mg/kg of body weight) characterizes the onset of impacts
Carcinogenic	Causes cancer; often, the dose-response function is characterized as a log-log correlation between dosage and the probability of observing cancerous cells
Mutagenic	Causes mutation of cells
Teratogenic	Causes changes in cells during prenatal development; may lead to birth defects or deformity

associated inferred health risk consequences are often acceptable. However, since these pollutants are directly related to human health effects, they receive focused attention by both regulatory agencies and the general public.

Incineration of wastes is viewed, not unexpectedly, as an important potential source of air toxics emissions since inevitably the mix of diverse materials called “waste” often involves contamination by trace metals. Further, wastes may include a variety of toxic organic compounds targeted for disposal or toxics formed as by-products of industrial preparation reactions. Incomplete combustion results in emission of the compounds and “daughters” with similar chemical characteristics. Finally, due to moment-to-moment variation of the feed and other parameters, the incineration environment can degrade from time to time thus allowing a “puff” of toxic material to escape. The combination of these possibilities leads to intense scrutiny of incineration regarding air toxics.

Table 10.14
Volatility temperatures for several air toxics metals (31)

Metal	Volatility temperature (°C)	Metal	Volatility temperature (°C)
Mercury	16	Antimony	660
Arsenic	32	Barium	849
Thallium	138	Silver	904
Cadmium	216	Beryllium	1216
Lead	627	Chromium	1610

Trace elements of concern (especially mercury, arsenic, beryllium, selenium, lead, cadmium, zinc, and hexavalent chromium) are emitted in proportion to their concentrations in the waste fired. The simplest approach to estimating metal emission rates is to assume that the relative proportions of the metal in the emitted particulate matter is the same as that of the metal in the total inorganic fraction of the feed. There are several potential weaknesses in this approach:

- Some metals are trapped in relatively massive bottom ash and are never emitted to any significant degree. The chromium in large pieces of stainless steel is an example of this.
- Some metals are emitted strongly relative to their concentration in the ash. These “enrichment factors” (1) between the metal content of the bulk ash and that in the content in the fly ash can exceed 200-fold. Mercury and its compounds are examples. Because of the high volatility of mercury, almost 100% of this metal is emitted from the furnace. Other metals show lesser but often significant degrees of emission enhancement. Barton et al. (31) ranked several key metals by their “volatility temperature,” the temperature where the sum of the vapor pressures of all species containing the metal present at equilibrium and weighted by their relative concentrations is 10^{-6} atmospheres (Table 10.14).

In a few instances, the balance between these and other factors influencing emissions has been studied and estimates can be made of the partitioning of feed metals between bottom ash and fly ash emissions (1).

Of the several air toxics, perhaps none has led to greater scrutiny nor impacted on regulatory acceptability than the several compounds from the family of polychlorinated dibenzo-p-dioxins (CDD) and furans (CDF). These complex chlorinated compounds included molecules with different degrees of chlorination (congeners) and, for a given congener, molecules where the chlorine molecules are located in different positions about the oxygenated benzene ring structure (isomers). Each of the congeners and isomers express their health effects to a different degree as shown in Table 10.15.

2.6. Fluid Mechanics in Furnace Systems

Furnace fluid mechanics are complex, with jet and buoyancy driven flows interacting in swirling, recirculating eddies, and all the while traversing complex geometrical sections. In a few instances, the flow field is laminar, but most situations are turbulent. Further, combustion of the fuel gases rising from beds of pyrolyzing waste results in heat release (and temperature change) of the gases. All of these phenomena are time and spatially variant. A basic understanding of several of these features of furnace flow, particularly the behavior of jets and of buoyancy effects, is of great assistance in the design and analysis of incineration systems.

Table 10.15
Toxicity equivalence factors (TEFs) for specific PCDD and PCDF compounds

	Equivalency factor (TEF _i)				
Positions chlorinated		International Eadon (32)	US EPA (33)	BGA (34)	Nordic (35)
Dioxins					
2,3,7,8 Tetra CDD	1.0	1	1	1	1
1,2,3,7,8 Penta CDD	0.5	1	0.2	0.1	0.5
1,2,3,4,7,8 Hexa CDD	0.1	0.03	0.04	0.1	0.1
1,2,3,6,7,8 Hexa CDD	0.1	0.03	0.04	0.1	0.1
1,2,3,7,8,9 Hexa CDD	0.1	0.03	0.04	0.1	0.1
1,2,3,4,6,7,8 Hepta CDD	0.01	0	0	0.01	0.01
1,2,3,4,6,7,8,9 Octa CDD	0.001	0	0	0.001	0.001
Furans					
2,3,7,8 Tetra CDF	0.1	0.33	0.1	0.1	0.1
1,2,3,7,8 Penta CDF	0.01	0.33	0.1	0.1	0.01
2,3,4,7,8 Penta CDF	0.5	0.33	1	0.1	0.5
1,2,3,4,7,8 Hexa CDF	0.1	0.01	0.01	0.1	0.1
1,2,3,4,8,9 Hexa CDF	0.1	0.01	0.01	0.1	0.1
1,2,3,6,7,8 Hexa CDF	0.1	0.01	0.01	0.1	0.1
2,3,4,6,7,8 Hexa CDF	0.1	0.01	0.01	0.1	0.1
1,2,3,4,6,7,8 Hepta CDF	0.01	0	0.001	0.01	0.01
1,2,3,4,7,8,9 Hepta CDF	0.01	0	0.001	0.01	0.01
1,2,3,4,6,7,8,9 Octa CDF	0.001	0	0	0.001	0.001
Other PCDD/PCDF	0	0	0–0.01	0.001–0.01	0

BGA: Bundesgesundheitsamt (German Federal Health Office).

2.6.1. Jet Behavior

The behavior of jets in furnaces is of particular importance in incinerator design. This importance reflects the function of jets in the following:

- The controlled addition of mass to contribute to the oxidation process, to act as a thermal sink to temper gas temperatures (air jets) or to convey refuse into the incinerator (suspension burning).

The controlled addition of momentum to promote mixing (turbulence) of the furnace gases to assist in attaining complete combustion (air or steam jets).

The behavior and design of jets in combustion situations is covered in more detail elsewhere (1, 16). The simplest jet system (the round, isothermal, turbulent subsonic jet) is reviewed here since it embodies many of the basic characteristics important in understanding the behavior of the sidewall air jets commonly used in mass-burning incinerators. The complexities of cross flow, combustion, nonisothermal flow, and buoyancy effects should be considered, however, in any final design calculations (1, 36–38). The round jet (Figure 10.6) shows three characteristic flow regions:

- The *mixing region* adjacent to the nozzle and extending about 4 to 5 nozzle diameters from the discharge plane, which contains, as a distinguishing feature, an undisturbed flow near the axis of the jet (the “potential core”) with a relatively flat velocity profile. The potential

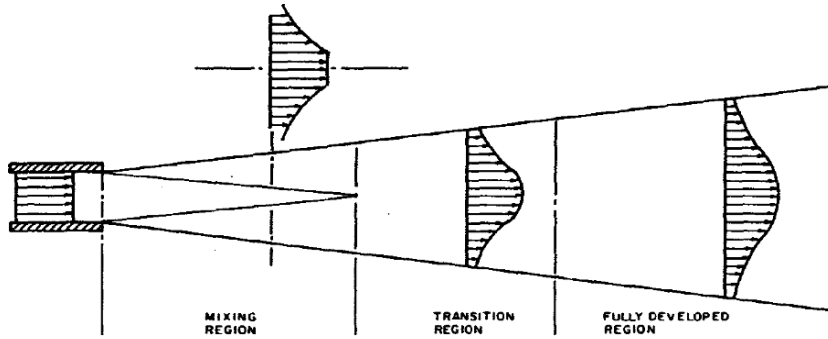


Fig. 10.6. Regions in jet flow.

core is surrounded by a flow field with a high-velocity gradient where the rapidly moving jet gases mix with the surrounding fluid.

- The *transition region* extending 4 to 8 diameters downstream where the radial velocity profile acquires a stable shape.
- The *fully developed flow region* where the normalized velocity profile about the jet axis remains of constant or self-preserving shape.

Important jet characteristics include (1) the change in centerline velocity and concentration (of nozzle fluid) with distance, (2) the shape of the radial velocity and concentration profiles in the fully developed region, and (3) the rate of entrainment of ambient fluid into the jet.

The following functional relationships (6) describe these characteristics using the nomenclature u and c for mean velocity and concentration, ρ for density, x for distance from the nozzle, d_o for the effective nozzle diameter, r for the radial distance from the jet centerline, and m for the mass flow rate. As for the subscripts, o denotes nozzle conditions, x denotes conditions at a distance x from the nozzle, a denotes conditions in the ambient fluid, and m denotes conditions on the jet centerline. Note that the “effective nozzle diameter” may be different from the physical orifice dimension. For example, if the jet issues from a circular hole in a sheet steel plenum, the effective nozzle diameter is about 60% of the diameter of the hole: the diameter of the *vena contracta*.

- Velocity

$$\frac{\bar{u}_m}{\bar{u}_o} = 6.3 \left(\frac{\rho_o}{\rho_a} \right)^{1/2} \frac{d_o}{(x + 0.6d_o)} \quad (25)$$

$$\frac{\bar{u}}{\bar{u}_m} = \exp \left[-96 \left(\frac{r}{x} \right)^2 \right] \quad (26)$$

- Concentration

$$\frac{\bar{c}_m}{\bar{c}_o} = 5.0 \left(\frac{\rho_o}{\rho_a} \right)^{1/2} \frac{d_o}{(x + 0.8d_o)} \quad (27)$$

$$\frac{\bar{c}}{\bar{c}_m} = \exp \left[-57.5 \left(\frac{r}{x} \right)^2 \right] \quad (28)$$

- Entrainment
$$\frac{\dot{m}_x}{\dot{m}_o} = 0.23 \left(\frac{\rho_a}{\rho_o} \right)^{1/2} \left(\frac{x}{d_o} \right) \quad (29)$$

These functional relationships indicate that the jet flow expands inside a cone-shaped envelope. Defining the boundary as that corresponding to a velocity one-half of that on the jet centerline, a cone of half-angle 4.85° is defined. The corresponding half-angle for concentration is 6.2° (6).

In the presence of strong cross-flow velocities such as the gas flow arising from grate-fired incinerators, the direction of the sidewall jet is “bent” in the direction of the cross-flow.

$$N_{\text{Re}} = \frac{\rho_o \bar{u}_o d_o}{\mu_o} \quad (30)$$

Dimensional analysis suggests that the coordinates of the dimensionless jet axis (x/d_o and y/d_o) should depend on the ratio of momentum fluxes in the external and the jet flow as characterized by the parameter M and the Reynolds number (N_{Re}), calculated using the following equations:

$$M = \frac{\rho_a u_1^2}{\rho_o u_0^2} \quad (31)$$

For turbulent jets in the Reynolds number range above 10^4 , correlations of experimental data suggest that the Reynolds number effects are negligible and that M is the controlling parameter. Patrick (39) developed a relationship describing the trajectory of jets injected normal to the cross-flow (with the jet centerline defined by the concentration of jet fluid) as:

$$\frac{y}{d_0} = 1.0 M^{1.25} \left(\frac{x}{d_0} \right)^{2.94} \quad (32)$$

Data show that the concentration axis shows a greater deflection than the velocity axis. This is due, perhaps, to the asymmetry of the external flow around the partly deflected jet as shown in Figure 10.7.

The relationships have utility in predicting the flow behavior of sidewall air jets. Indeed, the Bituminous Coal Research (BCR) method of overfire air jet design (38) is based on an assumed jet penetration depth (clearly, somewhat less than the width of the chamber) corresponding to a centerline velocity of 2.5 m/s as calculated using Equation 25. More elaborate jet design methodologies were developed by Ivanov (36) as described by Niessen (1).

2.6.2. Buoyancy

Since furnace gases are hot, buoyancy effects can result in substantial flow acceleration. Although often overlooked in furnace analysis, these effects can be of sufficient magnitude as to cause severe erosion damage or to greatly change the velocity field, thus influencing the penetration distance of sidewall jets.

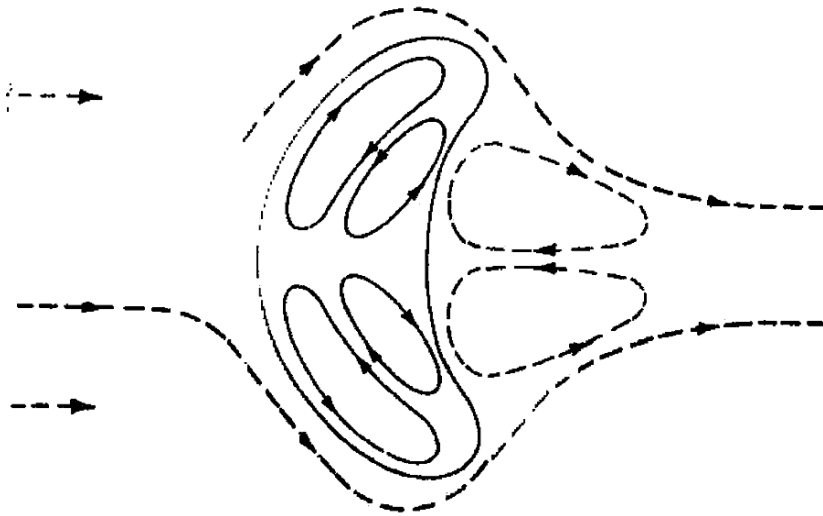


Fig. 10.7. Jet cross-section and circulation patterns for round jets in cross-flow.

The acceleration of gases from an initial velocity u_o , elevation y_o , and static pressure P_o is described by Bernoulli's equation:

$$u^2 = u_o^2 + \frac{2(P_o - P)}{\rho_o} g_c - 2g(y - y_o) \quad (33)$$

where ρ_o is the density of the gas and g_c is the acceleration of gravity (9.807 m/s^2). This equation has utility in estimating the buoyant acceleration of gases rising from the grate of an incinerator.

CASE 1

A well-sealed incinerator has a zone of hot gases arising from the grate and a cold zone of stagnant or slowly moving gases above the residue quench tank. The change in static pressure ($P_o - P$) for the cold gas, as the flow exits through a vertical outlet flue, is also experienced by the hot gas. Noting that the ratio of absolute temperatures is the inverse of the ratio of densities, writing Equation 33 for both flows and combining yields:

$$(u^2)_{hot} = (u_o^2)_{hot} + 2g(y - y_o) \left(\frac{T_{hot}}{T_{cold}} - 1 \right) \quad (34)$$

CASE 2

For many older furnaces, the furnace is leaky, so that there is an interaction between the hot and cold gases and the ambient atmosphere, with both gas streams accelerating, but with the acceleration of the hot zone being more pronounced. In this case:

$$(u^2)_{hot} = (u_o^2)_{hot} + 2g(y - y_o)_{hot} \left(\frac{T_{hot}}{T_a} - 1 \right) \quad (35a)$$

$$(u^2)_{cold} = (u_o^2)_{cold} + 2g(y - y_o)_{cold} \left(\frac{T_{cold}}{T_a} - 1 \right) \quad (35b)$$

EXAMPLE 6

In a large, well-sealed furnace, 6000 m³/min of gases leave the burning refuse bed at a temperature of 1100°C (1373 K) at an elevation of 12.5 m and at a velocity of 1.2 m/s. At the end of the furnace, 25 m³/min of quench tank vapors leave the furnace at 300°C (573 K) at 0.1 m/s.

The two gas flows leave through a vertical outlet flue at the top of the chamber (elevation 17.5 m, with an area of 65 m²). Estimate the average velocity through the flue as well as the possible peak velocity due to buoyancy effects. Neglect the flow area for the cold gases:

1. Mean velocity

$$\bar{v} = \frac{\text{Volumetric flow rate}}{\text{Flue area}} = \frac{6,000}{65} = 92.21 \text{ m/min or } 1.54 \text{ m/sec}$$

2. Buoyancy effects (Eq. 34)

$$(u^2)_{hot} = 1.2^2 + 2(9.807)(17.5 - 12.5) \left(\frac{1373}{573} - 1 \right) = 11.76 \text{ m/sec}$$

At this velocity, the gas needs only 6000/(11.76 × 60) or 8.5 m² of duct area. Thus, the flow cross section shrinks as the gas accelerates, exiting as a high-velocity stream on the side of the flue nearest the grate with a slowly moving mass of gas filling the remainder of the flue.

3. INCINERATION SYSTEMS FOR MUNICIPAL SOLID WASTE

The period from 1960 through 1990 marked the halcyon years of municipal incineration in the United States. The most significant driving forces behind the growth in installed incinerator capacity were as follows:

- Increasing urbanization leading to increased waste generation in the cities and increasing difficulty in locating landfill sites (the principal competitive waste management approach) near to the city centers
- Substantial increases in the per-capita waste generation pattern of urban Americans
- Expectations (not realized) that energy cost increases, as driven by oil prices and concomitant growth in the revenue realized in selling the byproduct electricity that provides a major mitigation of incineration cost, would continue

Incinerators handling large quantities of solid waste exhibit wide variation in design. These variations reflect local conditions, scale of operation, the state of technology, and, not unimportantly, the personal experiences and prejudices of the design engineer. In a study of incineration practice in the U.S. (7), over 20 major engineering firms and equipment vendors were asked to identify those design parameters that they believed to be broadly reflected in U.S. practice. Only one such parameter (the burning rate per unit area of grate) was identified.

Until the 1970s, incinerators in the U.S. were generally designed through a technical collaboration between the public works department of the owner city or county, their consulting engineer, and the major component vendors (especially, the grate, fan and refractory manufacturers). In most cases, the incinerators were operated by staff of

the public works departments of the owner city. The 1970s saw the emergence of a new paradigm: a system vendor who competed to design, construct, and operate the incinerator as a service to the owner community.

The incinerators operating in the early 1960s and earlier were relatively simple refractory chambers containing a grate to translate and mix (stoke) the waste. The combustion chamber was followed by very rudimentary air pollution control devices. The primary objective of these units was to achieve 80% to 90% volume reduction. Air pollution requirements focused on coarse particulate matter (“blackbirds”) and were not stringent. Usually, simple water sprays and settling chambers were sufficient to meet code. Although incineration was always a capital-intensive alternative to landfill, most of the cost was associated with civil works: foundations, buildings, chimney structures, etc. The technological risk for this kind of system was not high, although poor designs could lead to problems with refractory degradation, smoking, and high maintenance expense.

In 1970 the Clean Air Act was passed. This act required a significant upgrade in the sophistication and cost for air pollution control. The high air dilution of the leaky refractory furnaces (some operated at as high as 800% excess air at the stack) made addition of the new control systems (electrostatic precipitator technology was “borrowed” from coal-burning power plants) prohibitively expensive. The desire to minimize flue gas volume and the increasing value of electrical energy suggested a new incinerator design concept: the waterwall boiler generating superheated steam. This design eliminated infiltration air and, being inherently self-cooled, operation at low overall excess air levels was possible without undue slagging of the walls. Passing the steam through a turbine generated electricity and produced a new revenue stream to mitigate the burgeoning cost of the incinerator.

However, concurrent with these technological changes was a great increase in risk. In years past, minor design mistakes could be made and the “fixes” absorbed into the operating budget. Now a prospective incinerator owner community would have to consider plant investments often in excess of \$100 million and operating budgets that depended on a stable revenue stream from the electrical credit over a 20-year bond repayment life. Retaining a system vendor to design, build, and operate the facilities under a 20-year contract as a service to the host community appeared as a reasonable approach to contain and reallocate these risks. Importantly, this new project development and implementation concept recast the plant operations staff to one with standards approaching those of power utility operators. The working relationship between the community and the system vendor was codified and detailed in a comprehensive contract document—the service agreement. As one impact of these changes, the role of the consulting engineer shifted from one of being the engineering designer to project planning, preparing performance specifications for competitive procurement, providing technical assistance in financing, and securing permits. In other instances, entrepreneurial system vendors took the lead in developing projects.

The service agreement often goes beyond a simple documentation of a contract to provide waste incineration services. Since the lifetime of the agreement is often 15 to 20 years, many of the circumstances defining the nature of the service, economic factors, environmental requirements, and other important parameters will change. Thus, the agreement defines the set of reference system characterizations that were the basis of the original procurement and indicates methods and guidelines with which to update the

cost or performance basis from the baseline. The characterizations include a “reference waste” composition and heat content; unit costs for labor, utilities, taxes, and chemicals; environmental requirements; and daily and annual processing rates and energy recovery targets.

The new, system vendor-dominated incineration business employs a wide variety of designs to do the same job. This individuality reflects both the growth of incineration technology in recent years and the large number of basic design parameters that are somewhat flexible and can be bent to the prejudices of the design firm. The systems offered by the system vendors can be divided into two broad categories: mass burn technology and refuse-derived fuel (RDF) technology. Mass burn technology is the approach representing both the most successful and frequently implemented method for combustion of MSW. Mass burn implies the combustion of unprocessed solid waste. In contrast, RDF technology is based on combustion of a prepared, refuse-based fuel. The goal in RDF systems is to process the refuse to a relatively homogeneous material in order to achieve the degree of combustion control and low excess air operation found in coal-burning systems. However, by avoiding the considerable technical risks and cost of preprocessing the waste (except, perhaps, to remove oversize “bulky waste” and certain hazardous or undesirable wastes such as auto batteries) mass burn strategy gains a clear economic and reliability advantage. Nonetheless, although mass burn technology dominates the market in the United States and Europe, both approaches have their strong points and their advocates.

The performance objectives of a municipal waste incineration system are as follows:

- To process each normal operating day not less than the quantity of waste with an analysis and heat content specified in the service agreement
- To process the minimum weekly, monthly, and yearly quantity of waste specified in the service agreement
- To consistently operate within the emission limits and other legal constraints of all applicable environmental regulations to include restrictions on the concentrations or mass rates of air or water pollutants, sound pressure levels, and the maintenance of specified system operating parameters within designated limits
- To protect the health and well-being of incinerator employees and of the neighboring commercial and residential community
- To protect the capital investment reflected in the equipment, buildings, roads, etc. comprising the incineration facility such that the useful operating life and maintenance and operating expenses of the incinerator are not adversely impacted
- To meet any production guarantees regarding residue quality and quantity; export rates of power, steam or other energy-related products; or other commercial promises

The achievement of these objectives is strongly supportive of a healthy plant operation, good customer relations, and good financial performance.

Many of the most critical performance objectives are highly dependent on the characteristics of the waste and, most importantly, on the heat content. This importance derives from the fact that, in essence, an incinerator is a system to process heat. Although the capacity of incinerator plants are most often described in mass-based terms, the actual metric of capacity is intrinsically associated with their maximum heat release rate (the maximum continuous rating, MCR) and not a mass throughput rate (except as the mass rate, multiplied by the waste heat content, is equivalent to a heat release

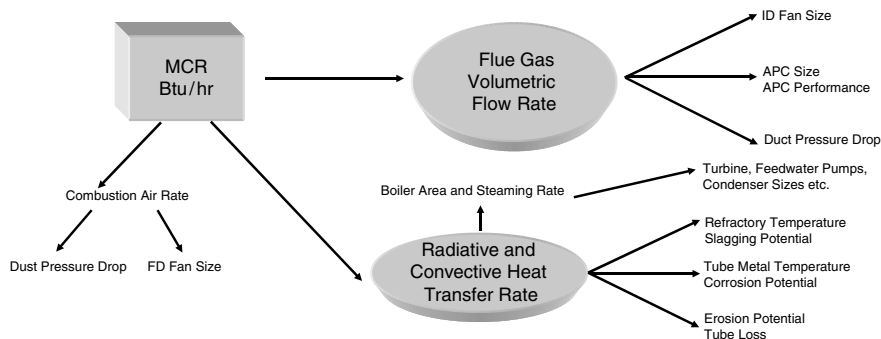


Fig. 10.8. Maximum continuous rating (MCR).

rate). Unfortunately, many municipal clients believe that their contract relationship with the incinerator operator is a commitment to process a given mass of material (e.g., 800 tons per day) rather than to process a specified number of millions of BTUs per day. Experience has shown that if this potential misperception is not clearly addressed in the service agreement, changes in waste heat content over the contract life will lead to customer dissatisfaction and even lawsuits.

Why is heat release the real variable? Figure 10.8 illustrates the process and hardware connections that spring from the MCR heat release parameter. Heat release rate, because of the approximate equivalence between heat release and combustion air quantity, is strongly related to the volumetric flow rate of combustion air and of the products of combustion. Thus, the heat release rate sets the size and horsepower of the forced draft and induced draft fans and the air pollution control system, and sizes the ductwork and dampers, pressure drops, etc. throughout the flow system. Also, the heat release rate, for a given combustion chamber, strongly impacts on the heat transfer rates (both convective and radiative), which affects the temperature of surfaces in boilers and on refractory walls. Thus, exceeding the design heat release rate can result in overheating of critical system components. All of these factors illustrate why incinerator capacity is quite properly equated to the MCR rather than the tons fed.

The firing diagram shown in Figure 10.9 provides a concise, graphical statement of the operating process envelope of a 800 ton per day incineration system. Specifically, the area bounded by the dotted lines represents the combinations of mass feed rate and refuse heat content that are supported by the referenced incineration furnace. For all points within the dotted area, the furnace can meet its design mass disposal rate and still remain at a technically sound fraction of MCR and the physical throughput limitations.

Let us consider the various elements of the boundary of the operating zone:

- **Maximum heat release:** The horizontal top line of the zone is the MCR. Heat release rates over this limit unduly stress the equipment or exceed design limits for fans, air pollution control equipment, etc. Also, in waterwall boiler systems, operation above this heat release rate may lead to boiler tube failures, tube erosion, etc. contributing to unscheduled outage.
- **50% of MCR:** The horizontal bottom line of the zone is set at 50% of the MCR. While somewhat arbitrary, burning at less than half of the design heat release is often accompanied by poor mixing within the furnace (increasing CO and hydrocarbon pollutant emissions), degradation in residue quality, furnace control problems, draft control problems, etc.

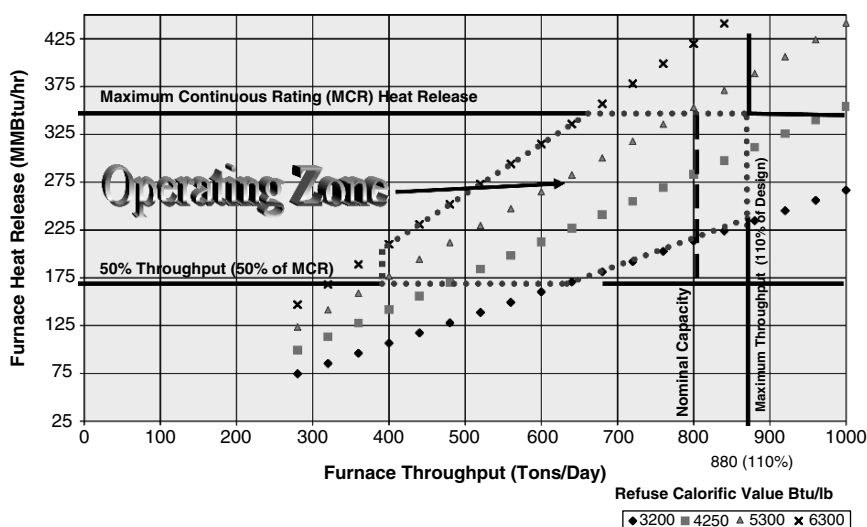


Fig. 10.9. 800 TPD incinerator firing diagram.

- 110% of maximum throughput: The vertical right-most boundary of the zone is set at 110% of the design mass throughput. This is a reasonable estimate of the maximum feed rate that can be accommodated by the structural strength and materials handling capabilities of the grate and the physical dimensions and capacity of the residue and fly ash handling systems.
- 50% of maximum throughput: The vertical, left-most boundary of the zone is set at 50% of the design mass throughput, reflecting the constraint that as the throughput drops from the design level, it becomes more likely that the grate will be exposed to furnace radiation. Also, the breakdown in the performance of the solids materials handling equipment becomes more likely.
- Maximum rate of highest heat content refuse: The sloped top boundary of the zone is set by the heat release throughput line for the highest plausible refuse heat content. This line intersects the MCR line at the design throughput. This is the maximum heat content refuse used as the basis of design in setting the MCR. Note that for this heat content refuse, the system can just meet the design throughput rate (often equal to the minimum rate set in the service agreement) and stay within the MCR.
- Maximum rate of lowest heat content refuse: The sloped bottom boundary of the zone is set by the heat release throughput line for the lowest heat content refuse that intersects the 50% MCR line and extends to the design capacity limit.

Since the operating zone described in the firing diagram is a simple, graphical statement of the maximum operational capabilities of the incineration system, there are merits to including the diagram as part of the service agreement.

Thus an incinerator can be and is many things. The subsections that follow outline very briefly the principal options in incinerator design. Any one topic would justify a chapter or a book in its own right if the topic were to be explored at a level of detail fully supporting design decision-making.

3.1. Receipt and Storage

The system used for the receipt and storage of raw refuse is of major concern to the design engineer. Since this portion of the plant interfaces with the entire refuse

collection system and in some cases with the individual citizen, the traffic patterns and dumping areas should be carefully thought out. Consideration must be given to the rapid processing of incoming vehicles (especially since refuse deliveries are seldom equally spread through the day) and to the safety of all parties concerned.

In larger mass-burning plants, refuse is received and stored in a pit below ground level. A traveling bridge crane with a clamshell, "orange-peel," or grapple-type bucket is used to pile and mix the refuse as well as to feed the incinerator furnace. The orange-peel and grapple-type bucket are the means most common in new plants. The capacity of the pit is generally equivalent to the quantity of refuse that can be burned in 2 to 3 days and, most certainly, from the time of the last receipt Friday evening until waste receipts begin again on Monday. Good pit design should provide for drainage, for fire control, and with means to recover and remove problem wastes that are discovered after dumping.

The crane operator is more than a cog in the materials handling system. The operator should be concerned with mixing of refuse to even out variations in refuse character, setting aside problem wastes (mattresses, engine blocks, refrigerators, and other "white goods"), moving refuse away from the dumping wall to allow uninterrupted dumping during peak receipt periods, keeping the feed hoppers filled, and planning the refuse withdrawals to effect a systematic cleaning of the pit. The latter responsibility is important for sanitation, good housekeeping, minimization of housefly nuisance (by processing refuse in a shorter time period than the larval-pupal cycle of the housefly), and the elimination of odors from decomposing refuse.

In some cases, a paved "tipping floor" serviced by a front-end loader or dozer blade-equipped vehicle is used to receive and charge refuse. In such cases particular attention must be given to frequent cleaning to avoid the hazard of a slippery and unsanitary floor area. Special concern should also be devoted to the selection of rugged tires for refuse handling vehicles (to avoid rapid wastage or blowouts) and in using heavy-duty radiators (to avoid dust clogging and overheating).

3.2. Charging

Most solid wastes usually have a low bulk density and include a substantial fraction of cellulose (wood, paper, cardboard). The low bulk density of these materials requires relatively large storage space and often involves rehandling of the waste (stacking) to increase storage capacity. Here is a summary of the materials handling options and problem areas in solid waste management facilities:

Step	Small plant	Large plant	Problem areas
Receipt	Manual scale	Automatic scale	Delays, queues
Storage	Floor dump	Pit	Cleanout, fires
Reclaim	Front-end loader	Crane/orange peel	Mixing
Feeding	Ram	Chute, ram	Jamming
Support	Refractory hearth	Metal grates	Overheating
Residue handling	Quench tank, belt	Quench tank, drag conveyor or ram	Jamming

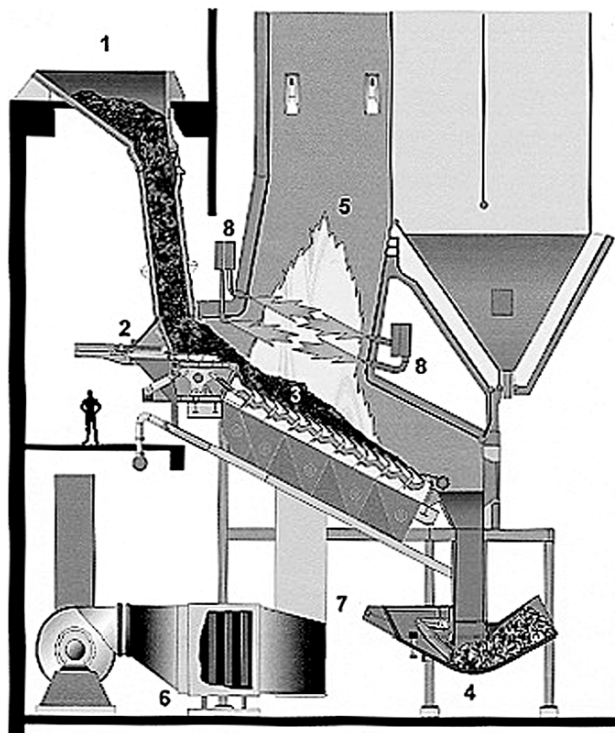


Fig. 10.10. Martin® municipal waste combustor. 1, feed hopper; 2, feeder; 3, Martin® reverse-acting grate; 4, Martin® discharger; 5, radiant furnace; 6, steam-heated air-preheater; 7, injection of underfire combustion air; 8, injection of overfire combustion air. (Courtesy of Ogden Energy Group, Inc.)

Feeding solid waste to a furnace presents special problems. It is critical to introduce the new waste using means that do not also allow large quantities of ambient air into the furnace. Such uncontrolled flows upset the draft, overly cool or quench the combustion so that unburned or incompletely burned material (products of incomplete combustion, PICs) are formed, and may result in rapid cooling of the refractory with consequent spalling. Also, combustion systems operate best with steady heat release rates. Uniform heat release results in uniform gas and refractory temperatures, and stable furnace draft (no “puffs” that push furnace gases into the operator’s work space), and are easier for the control system to follow.

In almost all large continuous mass-burning incinerator furnaces (>250 tons/day), charging is effected using a rectangular gravity-fed chute discharging to a feeding grate (Figure 10.10, item 1). The chutes are often water-cooled and are usually designed with a slight taper, opening toward the discharge, and with well-ground butt welds to avoid bridging. The base of the chute is generally fitted with a hydraulic ram feeder (Figure 10.10, item 2) to ensure positive and controllable feed of waste to the combustor. In small facilities, wastes are often dumped on a tipping floor and pushed about or stacked using a front-end loader.

3.3. Enclosures

A combustor consists of one or more of the following chambers (or zones):

Chamber	Function
Primary	Drying and gasification of solids, evaporation of liquids
Secondary	Burnout of soot, CO, residual organic matter
Afterburner	Temperature maintenance at levels where burnout will be achieved
Quench/cool	Gas conditioning to reduce temperature and/or humidify ahead of air pollution control

These chambers may be constructed in several ways depending on the size and basic concept (energy recovery or not) of the combustor:

Refractory: Formed from brick, special shapes or castable refractory and primarily appearing only in smaller and older incinerators. Key properties include abrasion, impact and corrosion (fluxing) resistance, refractoriness, and insulating qualities.

Water Wall: Comprised of water-filled steel tubes. The metal tubes comprising the wall panels are welded together with a narrow steel strip between the individual tubes to form a continuous, gas-tight membrane or water-wall. Key properties include abrasion resistance (along the grate-line of mass burning units) and corrosion resistance (attack from deposits and gases).

The chamber geometry is important as it affects the bulk gas flow patterns and heat re-radiation within the enclosure. Baffles, “bull-noses,” and other configurations are used to effect gross mixing, but induced turbulence using air jets is usually critical to the attainment of satisfactory mixing.

The floor of the furnace includes a refractory hearth (in small units) or, in all new and large plants, a metal grate or stoker that moves the refuse from under the charging chute and along the length of the incinerator’s primary chamber. Refractory material (usually of silicon carbide composition for its abrasion resistance and high thermal conductivity) is commonly installed at the grate line, often extending 3 to 10 feet above the grate. Frequently, the refractory cladding extends to about 30 feet above the grate to protect the waterwall tubes from accelerated metal wastage due to the changing oxidizing and reducing character of the gases arising from the burning refuse bed that sweep across the sidewalls.

The containment of combustion processes in the older refractory-lined chambers limited the peak temperatures that could be tolerated both to avoid degradation of the refractory and to control accumulation of slag on the walls. Also, air in-leakage cooled and quenched combustion along the sidewalls. This usually meant that refractory incinerators were operated at high levels of excess air (high flue gas volumetric flow rates) with consequent penalties in the cost of air-pollution control devices, fans, and stacks.

The waterwall boiler design resulted in a substantial reduction in overall excess air. As an often more important benefit, the withdrawal of energy as steam (usually as an intermediate to electricity) or hot water produced an important revenue stream to

mitigate the burgeoning capital and operating cost of incineration facilities. When steam generation is the desired objective, the incinerator enclosure design changes to maximize the fraction of the refuse heat content transferred to the water. Also, banks of tubes are immersed in the hot gas flow to recover heat convectively.

To better understand the system, let us follow the course of the water entering the boiler plant:

1. **Water treatment:** Raw water, containing dissolved minerals and suspended matter, would be an unsatisfactory feed to a boiler. To avoid scale buildup or corrosion from these contaminants, the water must be treated. The level of treatment increases with the severity of the water-side environment, as characterized by the temperature and pressure of the product steam. Treatment methods include filtration, softening, distillation, and ion exchange plus addition of chemicals.
2. **De-aeration:** Water also contains dissolved gases (air components, CO_2 , etc.), which would accumulate in the boiler. To remove most of the dissolved gases, the treated water is heated with steam or electricity to the atmospheric boiling point in a de-aerator. The water leaving the de-aerator is ready for introduction into the boiler using the feed-water pumps to raise the pressure to the boiler's working level.
3. **Boiler:** At the point of introduction into the boiler, the feed water is treated, de-aerated, and perhaps somewhat preheated such that its temperature is in the range of 100° to 200°C . In passing the water through the boiler, it is desirable to optimize the temperature difference between the water and the hot combustion gases (maximum heat transfer rate) to minimize the required amount of heat transfer area (capital cost) while still extracting the maximum amount of heat from the combustion gases. In larger boilers, this will include such components as the following:
 - a. **Radiant boiler:** These components are water walls or, in some cases, banks of tubes exposed to the combustion zone between which the hot flue gases flow. Heat transfer rates are very high, and radiant energy transport from the incandescent refuse bed, flame, or hot gases is the predominant means of heat transfer. The gas temperature leaving the radiant boiler zone is still quite hot, ranging between 1000° and 1100°C .
 - b. **Convection boiler:** The convection boiler consists of one or more banks of tubes (or "passes") between which the hot flue gases flow, and where the water (from the economizer) is evaporated. Flow through the tubes may result from buoyancy effects (a natural convection boiler) or pumps (a forced convection boiler) and is two-phase, containing both liquid water and steam. Heat transfer efficiency and boiler cost factors favor following the radiant boiler directly with the superheater; the heat recovery element where the gaseous steam generated in the boiler is further heated as a means of increasing its power generation potential. However, incinerators constructed in this configuration in the mid-1970s experienced severe corrosion of the superheater tubes. It was found that the accelerated corrosion was due to the deposition of chloride-containing ash on the superheater under conditions where the fireside (outside) tube metal temperature exceeded 315° to 370°C . While one can mitigate the corrosion by using more exotic metals or with special protective treatment of the tubes, it has been shown to be more cost-effective to precede the superheater with a portion of the convection boiler section such as to drop the gas temperature below 870°C . With the lower gas temperature driving force, the peak metal temperature in the superheater stays below the high corrosion threshold. The remainder of the convection section is, then, installed following the superheater.
 - c. **Steam drum:** The steam drum device consists of one or more large accumulators with disengagement space and mechanical devices to separate the gaseous steam from the

liquid water. The latter is recirculated to the convection or radiant boiler sections. The product steam, in thermodynamic equilibrium with liquid water, is saturated at the temperature and pressure of the steam drum contents.

- d. Superheater: The superheater is composed of a radiantly or convectively heated tube bank where, at (roughly) constant pressure, the steam is further heated to produce dry steam with heat content greater than that of the saturated steam. Such superheated steam conditions are often advantageous, since they will produce more mechanical energy in a turbine than will saturated steam or will tolerate moderate heat losses without condensation in, say, a steam-distribution system pipeline.
- e. Economizer: This component consists of one or more banks of tubes between which the hot flue gases flow and convectively transfer heat to the treated, de-aerated feed water. The feed water is usually not heated to the point where evaporation occurs. The economizer is located in the part of the boiler where the flue gas temperature is the lowest. Consequently, one must be careful that the dew point of the acidic flue gas components (both H_2SO_4 from oxidation of the SO_3 formed from a portion of the SO_2 generated in burning sulfur-bearing waste materials, and HCl and other halogen acids) is always safely below the temperature of the feed water so that condensation on the carbon steel tubes does not occur. Algorithms to calculate the dew point from the concentration of acid gases and moisture in the flue gases can be found in the literature (1).
- f. Air preheater: In some designs, the last step in heat withdrawal from the incinerator flue gases takes place to preheat the combustion air. Since incinerator flue gases often contain considerable moisture, one must be careful that condensation (and associated corrosion from the acidic components in the flue gas) does not occur during times when the ambient air is cold.

3.4. Grates and Hearths

All large municipal-scale incineration furnaces employ one of a variety of grates that stoke or mix the refuse during the combustion process in various ways depending on the type of grate or stoker. In smaller units, a refractory hearth or fixed array of static grate bars support the burning refuse. There are many different types of hearth or grate designs, each of which has its own special features. The more common concepts are described below.

3.4.1. Stationary Hearth

These incinerator furnace systems that operate without grates include the stationary hearth and rotary kiln types. The stationary hearth is usually a refractory floor to the furnace, and may have openings for the admission of air under a slight pressure below the burning material on the hearth (underfire air). In the absence of underfire air ports, air is admitted along the sides or from the top of the furnace (overfire air). It is usually necessary to provide manual stoking in order to achieve a reasonable degree of burnout. Stationary hearth furnaces are used for many smaller commercial and industrial incinerators. They are also used in crematories and for hospital wastes, when assisted with auxiliary gas or oil burners to maintain the furnace temperature above 650° to 900°C .

3.4.2. Rotary Kiln

Rotary kiln incinerators have been used at both industrial and municipal installations for disposal of combustible solids, liquids, and gaseous wastes. While municipal rotary

kilns normally handle only solid wastes, industrial kilns are generally designed for both solids (often including drums) with provision for firing liquid wastes. There has been little use of the rotary kiln for municipal incinerator furnaces except to provide additional residence time for improved residue burnout *after* the burning of refuse on a multiple-grate system.

The rotary kiln is a cylindrical, horizontal, refractory-lined shell that is mounted at a slight (usually less than 3%) incline. Rotation of the shell (usually at less than 2 RPM) causes mixing and “opening” of the waste, thus improving contact with the combustion air and improving combustion efficiency. Variable speed control is preferred to tailor residence time to waste characteristics. The length to diameter ratio of the combustion chamber normally varies between 2:1 and 10:1, and the peripheral speed of rotation is normally in the range of 0.3 to 1.5 m per minute. Kiln loading is usually in the range of 3% to 12% of the cross-sectional area. Combustion temperatures vary according to the characteristics of the material being incinerated but normally range from 815°C to 1650°C. Residence times of the solids vary from 20 minutes to hours depending on the nature of the residue, the kiln incline, the length of the slope, and the rotational speed (1). Kiln gases experience residence times of up to 3 seconds since, often, a large secondary combustion chamber is provided.

Although the rotary kiln approaches the waste management ideal of an “omnivore” (capable of processing all types of waste and in varying proportions), its inherent characteristics also limit its utility:

- **Size:** Kiln systems are most compatible with large waste disposal requirements. Although units are available rated as low as 750,000 kcal/h, the small units are more costly than the modular combustion unit (MCU) of equivalent capacity. A design limit of 800,000 kcal per hour per square meter of cross-sectional area is recommended so that even small capacity units are relatively large.
- **Stratification:** Kiln systems are prone to stratification of the gas flow. Induced jet mixing and a large secondary chamber are required. A design basis of 1 second mean residence time at 900°C (minimum) is recommended for the secondary chamber.
- **Particulate entrainment:** As the load rotates, a portion of the ash is lifted and then drops through the gas stream. Since all of the air for combustion must be introduced at the feed end of the kiln, gas velocities over the bed are also higher than for other systems. To minimize entrainment, gas velocities should be limited to 3 to 4 m/s. Measured uncontrolled particulate loading is much higher for kilns than for modular combustion units or other nonfluidized systems.
- **Maintenance:** Because of the severe abrasion, refractory life is usually limited to about 2 years. Shorter life is common when slag attack occurs or when the hardness of the superduty brick linings is not matched to that of the insulating brick used on the shell. Under the latter conditions, abrasion loss at the interface is rapid. In many plants, castable refractory is preferred, especially near the discharge seal where thermal spalling is common and frequent patching is required.

Selection of a rotary kiln as an industrial waste incineration system is usually based on its ability to incinerate a diverse range of waste types. Liquids, sludge, and solids can all be accommodated by the unit within the operating parameters dictated by design. Liquids can be directly pumped to the kiln where they are injected through burner nozzles located in the front wall. Automatic control modulates waste fuel flow to the

burners based on desired kiln exit temperature. A continuous pilot flame is usually provided to eliminate the possibility of flame failure during waste feeding. Liquids can be fed to the kiln from a variety of containers. Direct feed from on-site storage tanks is the most common method with the ability also existing to pump from tank trucks, small portable tanks, or steel drums.

Solids and semisolids can be fired in drums (usually but not necessarily limited to fiber packs), which are fed mechanically to the kiln through an airlock system. The feed rate of drums to the kiln may be under either automatic or manual control. Shutdown of the feed system usually occurs when there is a flame detected in the feed chute or temperatures in the feed lock exceed a preset minimum.

As the kiln rotates, the burned out material and ash travel through the kiln and fall into a water-filled quench trough. The water quenches the ash, which settles to the bottom of the trough. A drag chain conveyor removes the ash from the trough and conveys it to a closed bottom container for eventual landfill disposal.

The hot gases pass from the rotary kiln through a mixing chamber and into a secondary combustion chamber. Waste liquids may be burned directly in the secondary chamber as a supplement to, or replacement for, purchased fuel to maintain temperatures high enough (900° to 1100°C) to ensure complete burnout of distilled waste components. The secondary combustion chamber provides additional retention time (usually at least 1 second) and should include secondary air injection to induce mixing. The burners in this chamber are temperature controlled and have a continuous pilot flame to ensure uninterrupted combustion.

The hot gases pass from the secondary combustion chamber to a quench chamber, where they are cooled and large particles of ash are removed. The incoming gases are quenched through the use of water sprays, usually under manual control with automatic bypass in the event of water failure. The quench chamber is used to cool gases for introduction to a downstream scrubber.

A Venturi scrubber, typically with a variable throat opening, is usually installed downstream of the quench chamber. The cooled gases pass from the quench chamber to the high-efficiency Venturi scrubber. Recycle water backed up by makeup water is injected into the gas approach to the Venturi throat and is also sprayed directly into the throat. A remotely controlled damper can vary the cross-sectional area across the throat to achieve a range of pressure drops. Submicron particles in the gases are removed in this high-efficiency scrubber. Gaseous and liquid contaminants are likewise absorbed in the scrubber liquid. Water flow through the scrubber must be maintained at an optimum rate. Below this rate, scrubbing efficiency drops off rapidly. Above this rate, the efficiency increases only slightly, if at all. The scrubbed gases then pass through a liquid-gas separator; the entrained water containing the pollutants removed from the gas is separated from the gases and flows back to a recycle water tank. The gases proceed to an induced draft fan and out through the stack to the atmosphere. The induced draft (ID) fan is usually equipped with an adjustable inlet vane to regulate flow through the system. Water discharged from the quench chamber, scrubber, and demister usually flows to a recycle water tank where it is held for reuse.

As with any refractory-lined furnace system, the rotary kiln incinerator offers the best results when it is run 24 hours a day, 7 days a week on a continuing, steady-state basis.

3.4.2.1. TRANSPORTABLE CONFIGURATIONS

The cleanup of abandoned sites involving fixed quantities of hazardous wastes (such as the Superfund sites in the U.S.) is often found to be appropriate for the broad waste-type tolerance of the rotary kiln. However, the limited quantity of material available in such sites makes a permanent incinerator installation unfeasible. In such instances, the transportable rotary kiln has shown itself appropriate and cost-effective. Following on the successful performance of a “proof-of-principle” demonstration transportable kiln by the US EPA, a number of such systems have been deployed for the cleanup of small hazardous waste sites.

3.4.2.2. O’CONNER COMBUSTOR ROTARY KILN CONFIGURATION

In the 1980s, a new rotary kiln design emerged—the O’Conner combustor. The kiln was fabricated of boiler tubes with a space (<0.5 cm) between each tube. At each end of the kiln, the tubes are fitted to a toroidal steam drum with the same diameter as the kiln. At the discharge end, a number of tubes are assembled in a radial pattern to a central rotating seal. Air is forced through the space between the tubes so, unlike the conventional rotary kiln, heat release is distributed along the length of the kiln. Several O’Conner combustor municipal refuse incineration plants were constructed in the U.S., but the lead system vendor offering the concept withdrew from the municipal marketplace in the early 1990s.

3.4.3. *Stationary Grates*

Stationary grates have been used in small incinerator furnaces for a longer time than any grate system except the stationary hearth. The stationary grate is composed of cast metal or fabricated metal grates with, perhaps, provision for rotating the grate sections to permit dumping of the ash residue. Although some stoking action can be obtained by shaking the grate, stationary grates normally require manual stoking.

3.4.4. *Mechanical Grates: Batch Operations*

Mechanically operated grates installed in batch-type furnaces were a natural evolution from the stationary grate furnaces. Although batch-type incineration furnaces have given way to continuous furnaces for new, large installations, many of the new small-capacity incinerators still utilize batch-fed furnaces, either with stationary or intermittently operated grates or without grates, the latter in small commercial and industrial installations.

3.4.4.1. CYLINDRICAL FURNACE GRATES

In the circular batch furnace, the grates form annuli inside the vertical cylindrical walls of the furnace. A solid grate or “dead plate” covers the central area of the annulus. A hollow rotating hub with extended rabble arms rotates slowly above the circular dead plate to provide mechanical stoking or mixing. The rotating hub is covered with a hemispherical cone, and one or more consecutively smaller cones are stacked on top of the first one. Forced air (called “cone air”) for combustion is supplied through the hub to the hollow rabble arms, and thence through openings in the arms to the space just above the dead plate. Additional cone air is supplied to each of the cones in order to cool the metal. The annular grate area is divided into pairs of keystone-shaped segments;

each pair is arranged to open downward for dumping the ash residue into the ash hopper below. These segmental grates are either hand-operated or hydraulically operated.

3.4.4.2. RECTANGULAR BATCH FURNACE GRATES

Mechanically operated grates in rectangular batch-operated incinerator furnaces include reciprocating (pusher) grates and rocking grates. The grates are installed in a slightly inclined position from the horizontal, with the lower end of the incline at the ash discharge point. With these grates, the furnace is fed intermittently through an opening in the top and at the higher end of the grate, and the fresh refuse is deposited over the bonfire of previously ignited refuse.

As the burning continues, the grates are operated under manual control to move the burning bed of refuse toward the discharge, with manual control, ideally to prevent the discharge of residue that has not been completely burned. In some instances, a dump grate is installed at the ash discharge point to hold back ash residue that is still burning, with manual operation of the dump grate after the accumulated ash has been completely burned.

3.4.5. *Mechanical Grates: Continuous Operations*

Mechanical constant-flow grates are used in most of the newer continuous-burning incinerators. The constant-flow grate feeds the refuse continuously from the refuse feed chute to the incinerator furnace, provides movement of the refuse bed and ash residue toward the discharge end of the grate, and does some stoking and mixing of the burning material on the grates. Underfire air passes upward through the grate to provide oxygen for the combustion processes, while at the same time cooling the metal portions of the grate to protect them from oxidation and heat damage. Typical grate designs correspond to an average heat release rate of 13,500 kcal/m²/min. Clearly, the actual rate in different portions of the grate differs widely from this average.

3.4.5.1. RECIPROCATING GRATE

The reciprocating or pusher grate is, by far, the most frequently used grate system in modern incineration plants. The illustration in Figure 10.11 shows a common design strategy where alloy grate bars are installed stepwise in rows with no or a slight downward incline toward the discharge. In the flat or downward inclining approach, the rows of grate bars move alternately to push the refuse from the feed chute, through the combustion area to the ash hopper. Additional stoking and mixing (breaking open packed refuse masses) may be obtained by providing a drop-off (Figure 10.11, item 5), so the refuse tumbles from one grate section (step) to the next. Up to four grate sections are commonly included in this type of grate for a continuous flow incinerator.

In another design, (the Martin© reverse-acting reciprocating grate system shown in Figure 10.10), the grate surface is inclined at an especially steep angle. In the Martin system, the grate bars (Figure 10.10, item 3) push “uphill,” and due to the steep incline, the lower level of refuse is forced back against the gravity flow direction, a concept leading to vigorous stoking and internal “turbulence” within the bed, which breaks up the refuse mass and facilitates combustion.

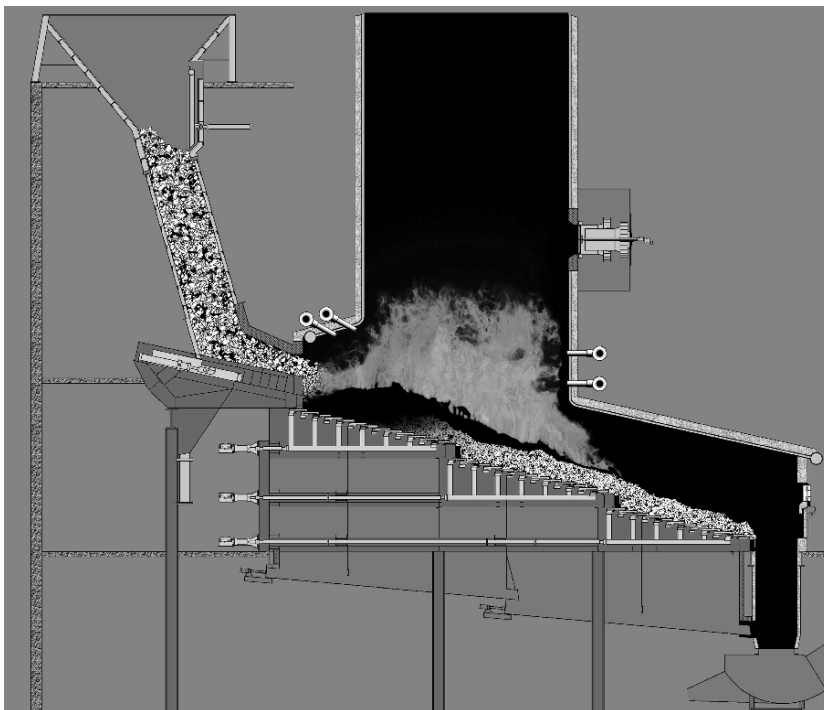


Fig. 10.11. Detroit stoker reciprocating grate furnace system. 1, refuse charging hopper; 2, refuse charging throat (refractory lined or water cooled); 3, hydraulic charging ram; 4, grates (high Cr-Ni alloy); 5, vertical drop-off (lined with alloy tuyeres to admit air); 6, overfire air jets. (Courtesy of Detroit Stoker, Inc.)

3.4.5.2. ROCKING GRATE

The rocking grate was a common design in the 1950s and 1960s in the U.S. This grate system also slopes downward from the feed toward the discharge end, with up to four or more grate sections installed in series, and with or without a drop-off or spill-off between grate sections. The rocking grate includes a multiplicity of grate sections or segments that are approximately quarter-cylindrical and include openings for undergrate air. These grates are arranged as successive “stair treads” with risers of less than 3 cm. Alternate rows of grate sections are rotated approximately 90 degrees about the edge toward the discharge of the grates, with the grate face rising up into the burning mass and thus breaking it up and thrusting it forward toward the discharge.

3.4.5.3. TRAVELING GRATE

The traveling grate was widely used in the 1950s and 1960s in the U.S. continuous flow mass burning incinerator furnaces. This grate type is still in use as the burnout grates in spreader stoker refuse-derived fuel (RDF)-burning boiler furnaces. There are two types of traveling grate stokers: the chain grate and the bar grate.

For continuous flow systems, both convey the refuse from the gravity feed chute through the incinerator furnace to the ash residue discharge, much as a conveyor belt.

Because the traveling grate stoker does not stoke or mix the fuel bed as it conveys, incinerator traveling-grate stokers are often cascaded in two, three, and even four or more units with spill-offs of a meter or more between grate sections. For use with a spreader stoker for RDF, the mechanical or pneumatic feeder “flings” the RDF material out over the burning refuse mass on the grate. The unburned fraction then falls to the grate and is drawn back toward the boiler face incorporating the feeder mechanism, dumping the ash through an air seal just below the feeder.

3.5. Combustion Air

The combustion air supply is critical not only to meet the stoichiometric requirements to oxidize the waste, but also to dry and gasify solids, atomize liquids, and induce mixing in the flow field. The air supply system is usually characterized as one or more of the following:

- Underfire air: supplied under the grates of mass-fired combustion units. Preheat may be used to assist in drying wet wastes, although only a fraction of the latent heat load for drying can be related to the heat content of the underfire air. However, if only a portion of the waste can be dried and subsequently ignited, heat release within the bed can provide the needed additional energy. Underfire air is also critical to cool the metal alloy grate bars, which otherwise would oxidize and degrade at the high temperatures ($>1100^{\circ}\text{C}$) achieved in the burning mass.

As discussed above, the gasification process (both full oxidation and partial oxidation to gaseous “fuel gases”) is driven by the underfire air. In mass burn systems, the underfire air rate is often close to the stoichiometric requirement. Air demands along the grate are uneven, leading to the use of several underfire air plenums to control the underfire air distribution along the grate. There is a concentration of gasification and air demand (far in excess of air supply) near the feed end of the grate (say, at 15% to 30% of the way along the grate) and limited air utilization in the discharge (ash cooling) zone.

- Atomization air: a term applicable to liquid waste burners relating to the (high pressure) air stream used to atomize the liquid waste. Steam may also be used if available.
- Primary air: a term usually applied to gas or liquid waste burners and relating to the air stream entering with the waste. Usually the design of the air supply system is such as to induce intense mixing of fuel and air. Swirling flows are often generated to increase mixing. The inducement of swirl results in the generation of a counterrotating axial flow moving back toward the burner tip, which carries both heat and reactive free radicals to mix with, dry, and ignite the incoming material to facilitate rapid initiation of combustion.
- Secondary air or overfire air: the air supplied to the gas stream following gasification. This air is usually supplied at high pressure (velocity) and in carefully researched locations and directions to induce mixing. Design features of secondary air jets include the stoichiometric implications (How much excess air will result from the introduction of the flow?), penetration (Will the flow penetrate the flow of gases from the primary zone without adverse impingement effects on the opposite wall or the fuel bed?), coverage (Will all of the primary zone flow be mixed by the secondary flow?), and turndown effects (Will the desired features of secondary flows be maintained adequately as the overall system moves off design conditions?).

In smaller incinerators, secondary air is often added at low velocity through slots or small openings in a bridge wall separating the primary chamber from the secondary chamber. In the latter case, mixing is dependent more on the shape of the chamber and changes in direction of the main gas stream than on the energy carried by the air jets. Low velocity

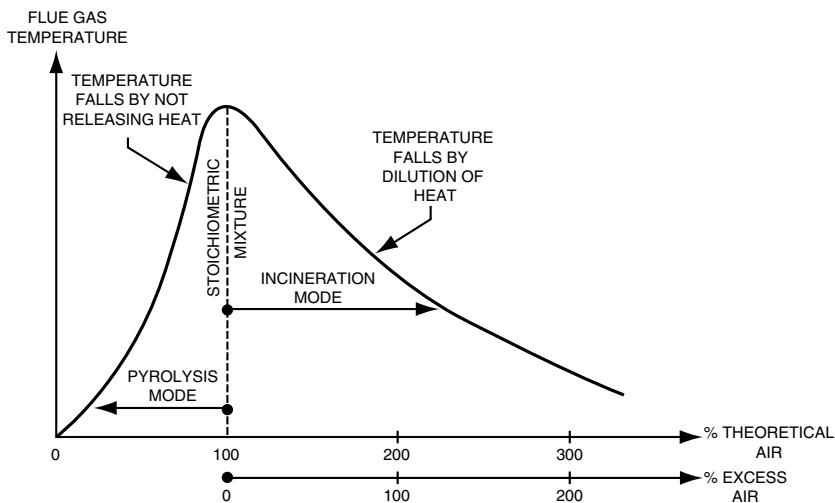


Fig. 10.12. Effect of excess air on flame temperature.

combustion air can also be admitted through furnace openings as a result of the negative pressure or draft within the furnace chamber. The quantity of combustion air admitted through such openings can be controlled by dampers or by the door opening.

- Tertiary air: additional air supply beyond secondary, which is used to cool the flue gases by dilution. Due to the high cost of air pollution control, this option for gas cooling is seldom employed.

Addition of air to a combustion system acts broadly in three ways:

- The air oxidant chemistry (oxygen content) interacts with the fuel value of the waste to release heat and increase the temperature, evaporate free water, and pyrolyze waste.
- The mass and specific heat of air components moderates the temperature.
- The momentum of the air flow acts to mix the furnace gases, thus facilitating complete combustion.

Figure 10.12 illustrates both the chemical effect (heat release is almost directly related to the proportion of the stoichiometric oxygen that is added) and the tempering effect. To the left of the stoichiometric mixture line, air addition increases the mean off-gas temperature by facilitating the release of heat. To the right of the stoichiometric line, the temperature progressively decreases by “dilution” of the heat (now fully released) by increasing the total flue gas mass rate.

3.6. Flue Gas Conditioning

Flue gas conditioning is defined as the cooling of the flue gas after it has left the combustion zone to permit discharge to mechanical equipment such as dry air-pollution control devices and fans or a stack. In general, cooling to 230° to 370°C is necessary if the gas is discharged to mechanical equipment, although cooling to 315° to 600°C is adequate for discharge to a refractory-lined stack.

Both wet and dry methods are used for cooling (or tempering) incinerator flue-gas streams. The following subsections discuss the technical and economic features of several embodiments of these methods.

3.6.1. Cooling by Water Evaporation

In wet methods, water is introduced into the hot gas stream and evaporation occurs. The degree of cooling is controlled by (1) the amount and droplet size of the water that is added to the gas and (2) the residence time of the gas in the water atmosphere. Currently, two types of wet cooling are used: the wet-bottom method and the dry-bottom method. Generally, the dry-bottom method is preferred.

In the dry-bottom method, only enough water is added to cool the gas to the desired temperature, and the system is designed and operated to ensure complete evaporation. A conditioning tower 9 to 36 m high is required and fine, high-pressure spray nozzles are used. Booster pumps are necessary to raise the water pressure to ensure fine atomization; water pressures from 6 to 36 bar are common in such systems. Alternatively, atomization can be effected using compressed air or steam. Control is usually accomplished with a temperature controller measuring the outlet flue gas temperatures and modulating the flow of water to the conditioning tower sprays.

The advantages of the dry-bottom system are that it minimizes water consumption, eliminates water pollution and discharge problems (the wastewater stream is generally quite acidic and contains numerous toxic metals), produces a dry effluent gas (free from entrained water), and reduces the volume of the flue gas. The disadvantages of the system are that it is expensive to design and install, power consumption is high, control is somewhat complex, and the small orifices of the atomizing nozzles make them susceptible to plugging. Also, the dry-bottom system is more costly than the wet-bottom system because of the need for water filtration and the maintenance required for the high-pressure pumps, nozzles, and control systems.

The wet-bottom method involves the flow of large quantities of water (much more than is required for cooling the flue gas). The water is supplied by coarse sprays operated at relatively low pressures. The excess water falls to the bottom of the cooling zone and is rejected or recycled. With recycling, the water approaches the wet bulb temperature of the flue gas.

The equipment used in this system consists of several banks of sprays, each with several nozzles with relatively large openings (over 0.5 cm), located in the flue leading to the stack or air pollution control equipment. Line water pressure is adequate for satisfactory operation. The system is generally controlled by measuring the gas temperature downstream of the sprays and modulating water flow, either manually or automatically.

The advantages of the wet-bottom system are that it is relatively simple, reliable, and inexpensive to design and install. Also, there is a reduction in total gas volume during cooling. A disadvantage of the wet-bottom system is that much more water (greater than 100% excess) is used than is necessary for cooling the gas. The excess water is acidified in use and is contaminated with particulate and dissolved solids. Also, the flue gas leaving the spray chamber may carry entrained water droplets or wet particulate

matter. These moist particles can cause operating problems with the air pollution control (APC) and fan equipment owing to fly ash adherence and accumulation.

3.6.2. Cooling by Heat Withdrawal

The second method of gas conditioning (assuming that the incinerator itself is not a boiler system) uses a convection water tube boiler in which heat is removed from the flue gas to generate steam or hot water. The equipment consists of a convection-tube waste-heat boiler and perhaps an economizer. In smaller units, a fire-tube boiler is common and low in cost. Most of the conventional boiler auxiliary equipment is required such as boiler-feed water pumps, steam drums, and boiler water treatment facilities.

The advantages of this system are that heat is recovered and that the shrinkage in flue gas is greater than with any other method discussed. No water is added to the system during cooling, which may or may not be desirable. The disadvantages of the method are that the system is expensive to design and install, the boiler installation is complex to operate, corrosion and erosion problems with the boiler tubes may occur, sticking of fly ash on the boiler tubes can occur, and reliable markets for the steam must be found or still greater investment is required for air- or water-cooled condensers.

3.7. Air Pollution Control

Concern of the public about air pollution impacts on the contiguous environment is probably the major factor affecting the decision of a community government to construct and operate an incinerator. The most noticeable forms of air pollution are fly ash, smoke, odors (from the stack as well as other areas), noxious gases, and dust. Another class of pollutants (the air toxics) is emitted in small quantities but is important because of the health impact potential. All emanate from an incinerator at times. However, stringent regulatory emission standards throughout the world (Table 10.16) and a strong response from the waste to energy vendor community in terms of system design/operating features and add-on control equipment make the level of modern incinerator emissions well below that which would present a significant health impact. Indeed, one often finds that an incinerator, viewed as a power plant, has an emission pattern (mass of pollutants per kilowatt hour) with significantly less impact than the fossil fuel fired power plants it replaces (40).

Although the flue gases from incinerators contain a number of pollutants, air pollution control (APC) equipment installed on these units is primarily directed at particulate removal. Note, however, that particulate control addresses a number of pollutants:

- Total suspended particulate (the inorganic ash materials elutriated from the combustion process, tarry aerosols of high molecular weight polynuclear hydrocarbons and soot arising due to incomplete combustion)
- Heavy metals such as cadmium, arsenic, lead, chromium, and nickel that are either part of the elutriated particulate or vaporized in the combustion zone and, later, condense (often on the fine particulate ash particles)
- Sulfur oxides, HCl, and other acid gases that have reacted with injected hydrated lime or limestone to form solid products (CaSO_4 , CaCl_2)
- Mercury and some of the heavy hydrocarbons (including dioxins and furans) that have been adsorbed onto activated carbon that has been injected into the flue gas stream

Table 10.16

International municipal waste combustor air emission codes (ca. 2003): all values corrected to 0 deg C, 101.3 kPa; 11 % vol O₂ dry unless otherwise indicated

Pollutant mg/Nm ³	Hong Kong best practicable means requirements	Germany 17 BimSCHV 1990 & France 10/10/96		Netherland BLA 93		Italy 20.8.94		Greece Turkey Rumania Bulgaria		Sweden Russia		U.S.		Taiwan (r)		Japan
		Germany TALuit 1986	10/30 (a)	5 (e)	10%	5	10	30	10	10	24 (h,i)	70	80–250			
		–	–	–	10%	10	–	–	–	10%	10%	10%	–			
Particulate	50	10	10/30 (a)	5 (e)	10	10	10	30	10	10	24 (h,i)	70	80–250			
Opacity	(v)	–	–	–	–	–	–	–	–	–	10% (i,j)	10%	–			
C-Org	20	20	10/20 (a)	10	10	10	10	–	–	–	–	–	–			
HCl	50	50	10/60 (a)	10 (e)	10	10	10	50	60	10	41 (i,j)	40 ppm _{dv}	(f)			
HF	2 (y)	2	1/4 (a)	1 (e)	1	1	1	2	1	1	–	7.3 (a)	–			
SO ₂	250 (x)	100	50/200 (a,b)	40 (e)	50	50	50	150	200	50	85 (k,m)	80 ppm _{dv}	–			
CO	100	100	50/100 (a)	50 (f)	50	50	50	100	–	100	125 (n)	120 ppm _{dv}	–			
NO ₂	400	500	200/400 (a)	70 (e)	150	200/NH ₃ <10	200	–	100	200	200 (l)	180 ppm _{dv}	(f)			
Dioxin ng/Nm ³	0.1	–	0.1	0.1	0.1	0.1	0.1	–	0.1	0.1	0.18 (i,o)	0.1	–			
Hg	0.2 (u)	0.2	0.05	0.05	0.05	0.05	0.05	0.2	0.03	0.01	0.08 (q)	0.3	–			
Cd	0.2 (u)	–	0.05 (c)	0.05	0.05	0.05	0.05	0.2	0.001	0.01	0.01 mg/dscm	0.3	–			
Total heavy metal	5 (w)	1.0/5.0	0.5 (d)	0.5 (g)	0.5	0.5	0.5	–	–	0.5	0.1 mg/dscm (p)	2 (p)	–			
Effluent from APC	–	yes until 1989	No	No	No	Yes but stringent quality limits	Yes	–	–	–	–	–	Yes			

Notes:

a. (daily average)/(1/2 hr average); b. SO₂ + SO₃; c. (Cd + Tl); d. (Sb, As, Pb, Co, Cr, Cu, Mn, Sn, Ni); e. Short-term average; f. 1-hour average; g. (Sb, As, Pb, Co, Cr, Cu, Mn, V, Sn, Ni, Se, Te); h. Metals as particulate; i. Stack test once per year; j. 95% reduction or 25 ppm_{dv} @ 20 deg C, 101.3 kPa, 7% vol O₂ dry; k. 80% reduct/on or 50 ppm_{dv} @ 20 deg C, 101.3 kPa, 7% vol O₂ dry; l. 6-minute average; m. Daily geometric average; n. 4-hour average for mass burn combustor; o. TEC presented in table above standard is 30 ng/dscm total dioxins; p. Total lead and lead compounds; q. 0.08 dscm or 85% control; r. All values corrected to 10% O₂ dry, 0 deg C 101.3 kPa; s. Total fluorides as F; t. Limit varies with district based in part on stack height; u. Total CD + Hg; v. Less than Rigelman shade 1; w. Nickel and arsenic and their compounds 1 mg/Nm³; x. H₂S, 5 mg/Nm³; y. Fluorine and its compounds 10 mg/Nm³, HBr. 5 mg/Nm³, phosphorus 5 mg/Nm³.

The process of selecting an optimal APC technology is complex. Defining the meaning of “optimal” requires consideration of several technical, economic, and other criteria:

- Pollutant removal efficiency (relative to all regulated pollutants and giving attention to the potential generation of new pollutants in the course of abating others)
- Capital investment:
 - Basic APC device and installation
 - Fans, pumps, and piping
 - Foundations and structural support
 - Ductwork to incinerator and to fan and stack
 - Insulation
 - Instrumentation and control systems
 - Electrical supply, motor control centers
 - Water supply, sewer, and portion of treatment system
 - Working capital in spare parts
 - Allowance for device replacement (useful life)
- Operating costs:
 - Operating labor
 - Special Costs for training in operations and maintenance
 - Operating parts and supplies
 - Absorbents, reagents, and similar consumables
 - Fuel
 - Electricity
 - Fan power
 - Pump power
 - Device power (especially for electrostatic precipitator but also for shakers, air compressors, etc.)
 - Water
 - Maintenance labor
 - Maintenance parts and supplies
 - Wastewater treatment and disposal
 - Ash treatment and disposal
 - Contract maintenance expenses (e.g., for instrumentation maintenance)
- Impact on incinerator availability (reliability) and capacity
- Operability and maintainability (including consideration of compatibility with general plant operating and maintenance labor skills, maintenance facilities and tools)
- Compatibility with layout limitations
- Compatibility with other regulations (noise, odor, illumination, visible plume, icing of adjacent roadways or electrical wires)

The detailed design and selection of APC systems is a major technical area in itself. Presenting such information is beyond the scope and objectives of this book. Details of design and performance with special application to incineration systems are presented elsewhere (1). A number of devices have been used over the years for particulate control, ranging in particulate removal efficiency from 5% to 15% (in the 1960s) to modern systems achieving upward of 99%. In light of current U.S. federal particulate emission standards, control efficiencies in excess of 98% are generally required.

At one time, simple settling chambers or expansion chambers were used in the breeching and flue gas ducts, and many of the older installations simply used refractory baffles across the breechings extending downward from the roof or upward from the bottom of the breeching to require the flue gases to pass under and over such baffles to settle the larger particles. In some instances, a coarse spray of water was directed into the flue gases and toward the baffles, with most of the water falling to the floor of the chamber without vaporization. The wet floor and baffles improved particulate removal by preventing re-entrainment of settled ash into the flue gas stream. At best, however, such systems only attained a control efficiency of 20% to 35%, far below modern requirements.

In the 1970s, a few plants installed high-energy scrubbers or cyclones, but the dominant move was to the dry electrostatic precipitator (ESP) that controlled particulate to the more stringent New Source Performance Standards arising from the Clean Air Act of 1970. The economics of the ESP were helped greatly by the emergence of the gas-tight water-wall boiler design that limited excess air (flue gas volume). In fact, the initial movement of incinerator construction to water-wall designs in 1970 to 1973 was primarily driven by the need to reduce flue gas volume, not to recover energy. By 1970, the ESP had already become dominant for European facilities.

In the mid/late 1970s, the regulatory spotlight in the U.S. shifted to the polychlorinated dioxin/furan compounds. The proper control technology for these materials focuses on upgrading the combustion environment. Burn out the precursors and there will be little or no dioxin. The data on emission factors suggests that combustion control, by itself, is an effective solution and that the dioxin problem is now well in hand.

In parallel with the dioxin/furan controls, the requirements for back-end treatment underwent a major change, extending the control requirement to include acid gases, most importantly HCl and SO₂. The solution to the requirement for acid gas control was the combination of the semidry absorber with lime slurry addition followed by a fabric filter.

Alkaline reagents show their highest utilization (low stoichiometric ratio of reagent to acid gas neutralization requirement) for a given level of control if the temperatures are low and if reaction time is long. These two process features led to the development, testing, and implementation of the spray dryer absorber–fabric filter control concept for application to resource recovery systems. In this technology, a large chamber is added following the boiler when the temperature has been reduced to, say, 230°C. At the top of the chamber, a water slurry of hydrated lime is injected through a spray dryer atomizer. The gas temperature and water quantities are kept in balance such that evaporation is rapid and complete in, say, 2 seconds or less. A conservative margin is added to the mean residence time to ensure a dry particulate as input to the bag house or ESP. Conservative specifications call for 18 seconds in a downflow configuration and 8 seconds in an upflow reactor (41).

In most facilities, pebble lime (CaO) is received in truck-load quantities and stored in a carbon steel silo. The total storage capacity depends on local supply availability and reliability, but is often a minimum of 14 days. The lime is slaked to Ca(OH)₂ using a minimum of two slakers, each designed for 100% capacity. Dilution water is added to the slurry in accord with the needs for exhaust temperature control for the spray dryer system.

Mechanical rotary atomizers have been used to produce a mist of finely divided droplets. Two-fluid nozzles are also used to form the fine droplets. Since the spray pattern from the two-fluid nozzles is narrower than that of the mechanical atomizers, the subsequent evaporation chamber can be designed with a smaller diameter.

The injected alkaline slurry and associated water evaporation has two effects: cooling of the flue gases from about 300°C to about 150°C, and the generation of a distributed field of acid absorbent particles (a mixture of CaO and Ca(OH)₂). Following the spray dryer chamber, the gas can be passed to an ESP or, more conventionally, a fabric filter. The ESP effects removal of the solid reactants (and other flue gas particulate). The fabric filter option accomplishes particulate removal, but also provides another opportunity for acid gas contact as the acid gases pass through the dust cake. About 15% to 20% of the removal occurs on the filter cake (42). The second contact opportunity not only increases reagent utilization and increases the ultimate removal efficiency but provides reserve alkalinity to respond to spikes in acid gas concentration. The spray dryer absorber–fabric filter combination has achieved above 95% HCl removal and above 80% SO₂ removal while accomplishing general particulate control to levels well below regulatory requirements.

In the early 1990s, attention moved to mercury and to the nitrogen oxides. Mercury can be controlled to an acceptable degree through injection of activated carbon ahead of the fabric filter. Injection of alkali sulfides (e.g., solutions of sodium sulfide) was also effective to bind mercury vapor but operational hazards with the sulfide makes the carbon option preferable. Activated carbon injection was also shown to be effective in reducing dioxin/furan and other high molecular weight hydrocarbons (PNH, PCBs) to levels below those achieved by combustion control. Modern plants also address nitrogen oxides control to the 50% to 65% level using ammonia or urea solution injection into the flue gases in the superheater region (selective, noncatalytic reduction [SNCR] technology).

Therefore, at present, optimum control for municipal waste combustors involves high-quality combustion controls and overfire air mixing to minimize CO, unburned hydrocarbons, soot (an important precursor to dioxin/furan species), and other PICs; urea/ammonia injection for NO_x control; activated carbon injection to adsorb mercury and its compounds as well as dioxins, PNH, and other high molecular weight compounds; a semidry spray dryer absorber for acid gas capture; and a fabric filter. This combination of operating practice and control equipment was followed with a tall stack to effect dispersion and avoid building downwash.

The direction of U.S. regulatory agencies in future years is difficult to predict. However, one might speculate that greater control will be required for metals and perhaps for nitrogen oxides. This could lead to the use of a dry followed by a wet electrostatic precipitator (replacing the fabric filter) with reheat ahead of catalytic, ammonia-based NO_x reduction. The fabric filters used in incineration systems generally use fiberglass bags, often with Teflon B coatings and thin film polytetrafluoroethylene membranes to enhance collection of very fine particles. Some plants with this APC flowsheet are already operating in Europe. One notes, however, that this APC train is considerably more costly than that in present use and that the ground-level pollutant concentration gains that are obtained are quite modest.

3.8. *Special Topics*

3.8.1. *Heat Recovery*

As fossil fuel and other energy costs increase, the economics of energy recovery from waste incineration improve in kind. For solid waste incinerator applications, however, particular attention must be given to the areas of corrosion, slagging, and other tube-fouling problems; irregularity of heat release in comparison to fossil fuel boilers; and reliability issues. One should carefully consider whether the recovered energy value exceeds the incurred capital and operating expense. Also, the decision maker should thoughtfully reflect on the impacts that energy recovery functions will cause in the most important and critical objective of the incineration system: reliable waste management.

Recovery of energy from the hot flue gases from waste incineration can be effected using several different types of equipment. Selecting among the alternatives depends on the scale of energy recovery, the sophistication of the work force, and the severity of the steam conditions (temperature and pressure) required. Alternatives include the following:

Water tube boiler

- Water wall primary furnace (radiant boiler)
- Convection tube bank (mixed radiant and convection boiler)
- Superheater tube bank (convection)
- Convection tube bank (convection)
- Economizer (feed water heating by convection)

Waste heat boiler

- Generally convection-based water tubes

Fire tube boiler

- Gases pass inside tubes immersed in a large, pressurized tank; these boilers are simple and low in cost but are limited to producing relatively low pressure saturated steam

Hot-water boiler

- Simple in design and produce high temperature hot water useful for heating or, with a secondary "step-down" heat exchanger, lower temperature general purpose hot water

3.8.1.1. ENERGY MARKETS

Energy markets are important to justify incorporating energy recovery into an incinerator design. Adding a boiler increases capital cost and decreases system reliability. Both adverse effects impact on the ability of the system to carry out its primary function: cost effective and reliable waste management.

Energy markets may be characterized in four ways: (1) The size of the market, (2) the energy type, (3) the reliability with which energy will be used (the market stability over the year), and (4) the reliability of revenues.

1. Market size: The best markets for waste-derived energy are large markets such that fluctuations in energy recovery or outright outages from plant shutdowns are readily

absorbed by other energy generators. Large markets of this type include electric utilities (serving an effectively infinite market and well backed-up) and major steam users (large steam-intensive manufacturing plants such as paper mills). Smaller users are often concerned about the reliability of energy supply and may demand backup, which negates the “avoided investment” value to the waste-derived energy supply and may even require a shadow workforce or warm-running to allow quick response to outages, thus negating a large portion of the savings by reduced workforces and maintenance expense.

2. Market type: The ideal market is a steam user. This avoids the need to install energy conversion equipment (turbo-generators), and the inefficiency in energy conversion for incineration plants that often operate at inferior steam conditions compared to a utility generating plant. Unfortunately, steam customers using the quantity of steam and the steam conditions (pressure and temperature) that are most compatible with an incinerator and that are located near to the incinerator plant (to minimize the acquisition of easements and the legal, cost, and energy loss impacts of long transmission lines) are often difficult to find.

Electrical generation has the advantage of being infinite in extent and assuredly continuing. The primary disadvantage is that there exists a highly efficient competitor (the utility itself) also generating electricity such that energy credits are minimal. Also, the capital investment in the energy recovery system may not be recoverable with a capacity credit associated with the sale of electricity unless the utility capacity is limited and the addition of the incinerator generating capacity has worth. Wheeling of your electrical energy product over utility lines is conceptually possible (for a fee) to tie in to a more attractive retail electrical customer. Often, issues of reliability of supply and legal challenges from the utility make this alternative unattractive. Wheeling is not a mandated service under present U.S. federal law and may be denied.

3. Market reliability: The solid waste problem (usually) knows little seasonality. Also, as with all combustion systems, continuous operation is strongly recommended to avoid temperature cycling of the equipment and refractory. Thus, the ideal energy market is 24 hours a day, 7 days a week, and 52 weeks a year. Although true for electricity, most steam markets fall short of this goal. Large steam users such as paper mills are the closest. Seven-day industrial operations of lesser size may be acceptable for much of the year. However, white-collar office buildings, school or office buildings, and other energy markets primarily using the steam for space conditioning show strong and unfavorable diurnal and seasonal patterns.
4. Revenue reliability: The financial lifetime of incineration systems is long. Therefore, energy marketing agreements will extend over many cycles of base energy cost (the cost of the reference fuel that is often specified in energy contracts and used to scale the unit value of the plant’s energy product, such as the cost of No. 2 distillate oil in New York). In some cases, contract terms at fixed prices may be obtained over relatively long times but usually at levels that are significantly lower than the more risky floating rates. On the other hand, if the unit value of energy floats, the project revenue stream is uncertain. This usually requires some kind of backing for the energy-related revenue stream if bonds (where the payment of principle and interest is based in part on the energy revenues) are used to finance the project. Also, most steam customers present a measure of risk that, in a time frame much shorter than the incinerator life, they may go out of business, cut back operations, or significantly improve their energy utilization patterns such that the steam market weakens or disappears altogether. Since such an evolution is always possible and is in the best interests of the steam user, few steam clients would agree to steam purchase agreements that limit their flexibility to make such changes. Thus, the risk of cessation of energy revenues hangs heavy over the heads of the incinerator operations.

3.8.1.2. CORROSION ISSUES AND ENERGY RECOVERY

Energy recovery components add to the unreliability of incineration systems. Clearly, part of the unreliability comes simply by the addition of another element in series with the incineration system that must work to make the incinerator operable. Further, however, the incineration process (as contrasted with the burning of fossil fuels) creates corrosive, fouling and erosive conditions in the flow path, which significantly degrade the availability and working life of boiler components, thus increasing outage frequency and severity and maintenance expense.

Corrosion of water-wall and tube metal surfaces is perhaps the most serious technical problem in the design of refuse-fired boilers. In the operation of a boiler using wastes as fuels (and for conventional liquid or solid fuels as well), metal wastage owing to corrosion and erosion and tube fouling owing to the buildup of deposits have presented serious problems to the system designer and operator. Detailing the nature and cures for such problems is beyond the scope of this chapter and is still a matter of intense study and speculation. Several basic concepts, however, merit qualitative description:

- Low-temperature corrosion: Condensation of moisture from flue gases occurs in regions of the energy recovery system where the surface temperature exposed to the flue gases falls below the dew point. This can occur with a too-low feed water temperature in the economizer or when cold ambient air overcools the surfaces used to transfer heat to incoming combustion air in the air heater. Condensation can also occur in “dead zones” in the air pollution control system and ducting where the circulation of (hot) flue gas is slow in corners or other low-flow zones such that heat loss to the ambient significantly reduces the metal surface temperature. Also, condensation can occur in an uninsulated stack when high winds and cold ambient conditions result in wall cooling below the dew point. The presence of mineral acids (especially sulfur trioxide or sulfuric acid) in the flue gas increases the dew point considerably above 100°C. If condensation occurs, the resulting metal wastage rate, accelerated by the presence of soluble chlorides or acids, can become unacceptably high. Clearly, this corrosive mechanism is always operative during boiler startup and shutdown unless fossil fuels are fired to warm up the unit. Algorithms to estimate the acid dew points are available in the literature (1).

The cure for this type of corrosion is straightforward, namely, to design the system so as to avoid dead zones and to maintain metal temperatures safely above the dew point of the flue gases. Furthermore, frequency and duration of cool-downs should be minimized.

- High-temperature corrosion: In regions of the furnace where the flue gases are above, say, 870°C, a variety of mechanisms for chemical attack of the metal tube surfaces can become operative. Chlorine, appearing in the flue gases as hydrochloric acid (e.g., from the combustion of chlorinated hydrocarbon wastes or PVC), or in salts such as sodium or potassium chloride, has been shown to participate in corrosive attack of metal tubes. Sulfur, appearing as the dioxide or trioxide or as sulfates, appears to slow the rate of attack of the metal by chlorides (43). Although the exact mechanism of attack is still in question, it is clear that fireside metal temperature is the single most useful parameter with which to judge the potential for rapid metal wastage. The flue gas temperature, however, is a second, though less direct variable at gas temperatures of interest.

Data reported by staff at the Battelle Laboratories (43–49) indicate that a maximum fireside metal temperature of about 200°C should give long (say, 15 years) carbon-steel boiler-tube service for systems burning 100% municipal refuse. Allowing for a 30°C temperature drop across the tube wall (a reasonable average for boiler tubes containing

liquid water and thus experiencing a high heat transfer rate on the inner wall, but about half of that experienced by superheater tubes containing gaseous steam), this corresponds to a maximum (saturated) steam pressure of 30 bar. For higher pressures and temperatures, increased wastage must be accepted or more costly tube metal alloys must be used. The problems of metal wastage are of special concern for superheater surfaces. The lower heat-transfer rates of the steam (compared to liquid water) results in higher fireside tube temperatures and greatly accelerated corrosion. Some relief from this problem has been found by inserting a portion of the convective boiler surface ahead of the superheater to lower the gas temperature and the use of rammed silicon carbide type refractory coatings on the tubes (50). The latter solution comes at the cost of lowered heat transfer rates and increased investment and maintenance expense.

- Oxidizing and reducing corrosion: In the combustion of highly non-ideal fuels such as raw municipal refuse and especially for mass-burning systems, the gases rising from the grate fluctuate in composition between oxidizing (having an excess of oxygen) and reducing (having an absence of oxygen and the presence of carbon monoxide, hydrogen, hydrocarbon gases, etc.). Tube metal surfaces exposed to such changing gas compositions are subject to rapid wastage. During the oxidizing period, the surface metal oxidizes to, say, Fe_2O_3 . When the gas switches to the reducing side, the oxide is reduced to the metal but the metal thus formed is not adherent and flakes off. The process repeats and net metal loss occurs. Flaking of the weak, reduced metal structure is accelerated by the “shot blasting” effect of erosion from particulate matter entrained in the gas stream.

In mass-burning systems, the bed processes always produces reducing gases and, consequently, sidewalls and radiant tube banks are particularly prone to this type of attack. Protection of the sidewalls with refractory up to a distance of about 10 m above the grate line has been used successfully to cure the sidewall corrosion problem. Introduction of sufficient secondary air above the fire and stimulation of high levels of turbulence can greatly assist the burnout of reducing gases prior to their entry into the initial convective tube banks.

- Abrasion (erosion) wastage: The mechanical erosion of tube surfaces by fast-moving fly ash particles can rapidly lead to tube failure. The fly ash from municipal refuse combustion has been shown to be particularly abrasive, more than that from, for example, most coal ash. This problem can be mitigated by designs that keep the velocity of the flue gases between the tubes below, say, 3.5 to 4.5 m/s; by coating the tubes with refractory (or letting slag build up to a degree); and by careful design of tube bank geometry and flow patterns. In general, however, these remedies lead to larger, more costly boiler facilities.
- Slagging: Slag buildup is not directly responsible for tube wastage. Indeed, slag accumulations act to protect metal tubes from erosive metal losses. Slag accumulation, however, reduces heat transfer rates and increases the pressure drop and gas velocity (erosion rate) through the boiler flues. Also, important corrosion reactions occurring under reducing conditions (in the absence of oxygen) have been shown to occur within the slag layer so that slag buildup cannot be used to infer a lack of chemical attack.

Slagging can be avoided by designs that maintain fireside metal temperatures below the range where the slag becomes tacky. For municipal refuse, this range is approximately 600° to 700°C . Commonly, the boiler passes are equipped with soot blowers that periodically use jets of steam or compressed air or blasts of metal shot to dislodge adherent slag. Note, however, that cleaning the tube surface can also result in the removal of coatings that were performing a protective role with respect to erosive or corrosive tube attack. Thus, following soot blower activation, wastage will be initiated, typically at very high rates, until a protective coating of slag or corrosion products is reestablished. Table 10.17 summarizes the corrosion and slagging problems in boiler systems that are commonly experienced by incinerators.

Table 10.17
Corrosion regimes in incinerator boiler systems

Component	System slagging	Chloride corrosion	H ₂ SO ₄ corrosion	HCl corrosion	Oxidizing- reducing corrosion
Sidewall	•	•			•
Superheater	•	•			•
Convection boiler		•			
Economizer			•	•	
Air heater			•	•	
Stack			•	•	

3.8.2. *Burning in Suspension*

Although the mass burn concept inherently avoids the cost and problems of handling and processing raw refuse, the combustion process on the grate is paced by the drying of the incoming refuse and mechanical opening of the mass to expose the combustible material to air. These steps tend to reduce the combustion intensity (kcal/hr/m³), thus requiring a larger and more costly combustion space. Further, the combustion, grate cooling, and air flow requirements of mass burning systems lead to operation at a relatively high overall excess air level within the furnace (more than 85% excess even in modern facilities). High excess air operation increases the size of the boiler, the air pollution control systems, the induced draft fan, and the stack. If the waste is particularly wet (e.g., a watermelon or wet paper), one may find essentially raw waste in the ash discharge conveyor.

These problems can be mitigated by first processing the waste to reduce the particle size; separating “heavies” such as rocks, china, metal objects, and the like; and then mechanically or pneumatically injecting the processed refuse-derived fuel (RDF) into a furnace. Depending on the trajectory and the thermal environment into which the waste is injected, the waste may burn partially or entirely while it is airborne. Ultimate burnout (if required) may require a “burnout grate.” In practice, this is accomplished with either a spreader stoker-fired system (sometimes called semi-suspension burning) or a true suspension-fired system such as is used for powdered coal.

In either case, the refuse is received and stored and then subdivided using a hammer-mill, rasp, or other device. If it is desired to reduce the quantity of residue, to minimize problems owing to the buildup of slag deposits or to recover unincinerated ferrous metal, the shredded refuse may be processed to (1) reduce massive residue content, (2) reduce (somewhat) fine residue content, (3) increase mean heat content, (4) recover ferrous metal using a belt magnet, and (5) simplify and reduce problems with transport of the processed refuse. The processed refuse is then stored for later retrieval or fed directly to the furnace using either belt or other mechanical conveyors, or a pneumatic feeder.

3.8.2.1. SPREADER STOKER

In a spreader stoker-fired system, the raw waste is first processed to a 10- to 15-cm top-size RDF, which is then bunkered. The RDF is then reclaimed from storage and projected into the incinerator enclosure using a rotating, vaned “flinger,” or is pneumatically blown in. The trajectory of an entering refuse particle carries it over a flat traveling grate stoker

moving the bed of burning residue back toward the firing face. The burned-out residue is discharged just below the firing chutes. Hot gases rising from the burning refuse bed and radiation from airborne burning particles rapidly heat the incoming refuse, drying and igniting it. The refuse particle may be entirely burned out while suspended in the gas or be swept out of the furnace. If the particle is large and heavy, it falls to the grate to aid in the drying and ignition of incoming refuse. Both burning patterns are desirable to provide ignition and to protect the grate. Thus, extra-fine shredding is avoided, a benefit since shredding costs rise rapidly as product top-size decreases (1). Due to the improved contact between waste particles and the combustion air, the combustion air levels can be reduced to approximately 50% excess air (overall).

Experience in spreader stoker firing of RDF has been generally acceptable, although most plants have experienced extensive startup problems associated with waste processing and RDF storage, reclaim, and feeding. These problems have resulted in increased capital costs (often more than 20% increase over the initial budget allocation) and losses in the startup period due to unrealized power revenue and waste processing fees.

A second problem that has shown itself with the spreader stoker systems is an increase in the dioxin generation in these plants in comparison to the mass burn facilities. The underlying mechanism underlying the increase appears to be the higher concentration of partially charred organic matter (carryover from the injection process) in the flue gases leaving the high-temperature zones. This graphitic char reacts with inorganic chlorine salts in the presence of certain heavy metals that act as catalysts to form dioxin species in the downstream zones of the incinerator.

3.8.2.2. SUSPENSION BURNING

In a suspension-fired furnace, the RDF is processed to a smaller (say, 5-cm top-size) refuse fragment than is the case for the spreader stoker. This significantly increases the processing cost (1). The RDF is pneumatically blown into the system and almost all burning occurs while the refuse particle is suspended in the hot furnace gases. To ensure that this occurs, tall furnaces (similar in dimensions to anthracite coal fired boilers) are used or a high degree of refuse subdivision is required. Often, a small burnout grate is provided in the floor of the furnace to increase the retention time for larger wood fragments or exceedingly wet refuse materials that survived the subdivision processing steps.

Suspension burning is well adapted to burning several fuels, and indeed most suspension burning of refuse (up to 20% of the total heat release rate) has been in co-firing applications with coal in large (> 100 MW) steam electric plants. Long-term experience involving co-firing with coal has demonstrated the following:

- No significant reduction in the performance of the electrostatic precipitators used for air pollution control
- No marked increase in boiler corrosion or tube fouling when burning upgraded RDF with precombustion removal of a large portion of glass and “heavies” using an air classification step following shredding
- Rapid burnout of most refuse particles, but a clear requirement for a burnout grate
- Significant problems with refuse feeding systems owing to the tendency of the RDF to bridge, jam, and hang up and to the high abrasiveness of the refuse

Combustion air for suspension burning, without main grates, requires a different consideration from combustion air for a grate system. In suspension burning, the air that conveys the shredded refuse into the chamber may be half or all of the theoretical air required for combustion; however, it must be sufficient to convey and inject the shredded refuse into the furnace. The technology of Combustion Engineering Inc (Winsor, CT), involves addition of air at points in the corners of the furnace chamber targeted tangential to an imaginary cylinder in the center of the boiler pass. This creates a cyclonic action, with the burning mass in the center of the rotating cyclone and the air injection surrounding the cyclonic flame. If the suspension burning system includes an auxiliary grate at the bottom of the furnace chamber for completing the burnout of the ash residue, a small amount of underfire air is desirable through this grate.

3.8.3. Residue Processing and Disposal

Municipal solid waste includes inert materials that cannot be destroyed in the combustion process. Also, the incineration process is inherently imperfect so that some potentially combustible material is dried, heated, and carbonized but the desired next step (gasification of the char) is not achieved. Further, some material simply “falls between the cracks” (siftings) and leaves the hot combustion environment substantially unburned. These three components comprise *bottom ash*, the inevitable residue of municipal solid waste incineration operations.

In addition, there is *fly ash*, the fine ash that becomes airborne in the primary chamber and either settles in the ducts and devices of the incinerator or ultimately becomes the inlet loading of particulate matter to the air pollution control system. Also, the fly ash includes refuse constituents that volatilize in the high-temperature zones of the furnace and subsequently condense on particulate (often the small diameter particles that present a large surface area). These may include heavy metals and high molecular weight hydrocarbons with a significant health effect.

The presence of ash imposes several technical and economic stresses on the incineration operation and the incineration business:

- Since ash is a solid and cannot simply be drained from the incineration system, costly high-maintenance devices are needed to remove the solids from the combustor and to handle the ash stream.
- Ash (especially the smaller particles in the fly ash) is a concentrate of toxic elements such as lead, nickel, and mercury as well as elements that are both carcinogenic and toxic, such as cadmium, hexavalent chromium, and arsenic.
- Ash constitutes a waste stream of the incinerator, and a place must be found to get rid of it. This generates a continuing operating cost for both transport to its disposal site and for the disposal itself. Potentially, landfill disposal leaves the incinerator firm with a liability for groundwater contamination and other adverse short- and long-term consequences of residue disposal.
- Ash hazards (real or imagined) have emerged in many countries as a significant concern among the public and the regulatory agencies. These concerns can be addressed, but they can be an impediment to project implementation.
- Ash (especially bottom ash) is not an especially desirable material. It is quite variable in its properties including both large clinkers and fine dusts, it may include both massive and wire-form metals and ceramic and stony materials, and it exhibits a variety of colors, mechanical

strengths, and other physical and chemical properties. Other than by the extraction of ferrous metal (easy to accomplish with a simple magnetic separator), processing the residue to adjust its properties to meet the demands of the marketplace can be quite costly in comparison to the modest revenue stream that can be expected.

All of these factors can be important in making the environmental assessments, developing the operating strategy, and carrying out the economic analysis concerned with municipal solid waste incineration. Understanding the practical technical alternatives, the legitimate environmental concerns and the realistic economic factors associated with ash management is an important element of design, operations, and business planning for refuse incineration.

The residue from the mass burn incineration of municipal refuse contains partially oxidized metal, glass and ceramics, inert mineral matter, and some unburned and partially burned organic material. Ideally, the combustible fraction is small. Practically, however, wet refuse components, incompletely burned heavy wood pieces, unbroken compacted masses, and the like will be found in the residue conveyor. The residue is most commonly trucked to a landfill for disposal. The weight of residue usually comprises about 20% of the refuse fired (dry basis), but its volume (assuming reasonably efficient burning) is less than 10% of the original refuse volume. The requirements for landfills receiving incinerator residue do not differ greatly from those for raw refuse, although gas formation is quite limited. The leachate characteristics are predominantly related to the metal and salt constant rather than to the organic matter. This latter characteristic is important since without the pH drop due to the organic acids formed during biodegradation of organic matter in the fill, the solution rate of the metals in the residue is very slow.

Incinerator residue may be readily processed by use of, say, a 2-cm-opening trommel screen and magnetic separator to produce three products: (1) ferrous metal, (2) mixed glass and (primarily) inorganic fines, and (3) oversize.

- The ferrous metal product, though inferior to the ferrous metal recovered from raw refuse, can be sold on the scrap metal market. The primary reasons for the lower quality of this material include its partially oxidized state, the mechanical trapping of impurities by the collapse of cans and other light gauge metal in processing, and the alloying of copper, tin, and other metals that occurs in the incineration environment.
- The mixed glass and fines product is useful as a fill and has been used in Baltimore (with further size separation) as an aggregate for road topping ("Glasphalt").
- The oversize fraction, importantly containing the unburned combustible, can be reburned or landfilled.

3.8.3.1. ASH CONVEYANCE AND DISCHARGE

Except for the case where shredded solid waste is burned in suspension, most solid incineration systems require means to convey ash through the furnace and to discharge it from the system when it is burned out. In mass burn systems, conveyance through the system is accomplished using moving grates. The normal gravity flow effects movement of both waste and ash through kilns. In the smaller modular systems (described below), a ram pushes waste into the system and, thereby, displaces ash. In a few smaller batch-type systems, the residue accumulates in the furnace until it exceeds some set volume limit or until the feed is exhausted. Then, after cooling, the residue is shoveled out.

Continuous removal of ash creates a problem if, even intermittently, a relatively large gate, “bomb bay,” or other opening is made through which the residue dumps out. In such circumstances, great volumes of cold ambient air may be pulled into the system, thus greatly disturbing the balance of pressure in the furnace, often temporarily cooling and quenching combustion and overloading the air pollution control device. In modern systems, these instances, however short, are unacceptable.

For granular residues, double flapper valves activated by gravity or (preferably) by sequenced pneumatic cylinders will allow solids to escape without disturbing the furnace. For larger residue objects (continuously or on occasion), the residue chute can be fitted with a normally open gate and mated to a removable container. The gate is closed to change containers, and careful attention must be given to the design and to the operating practice to avoid overheating, overloading, or jamming the gate.

More commonly, residue is dumped into a water-filled quench tank fitted with a drag chain conveyor or pusher ram (see Figure 10.10, item 4). The water both stops combustion and forms an air seal. In systems with the pusher ram, the ram, periodically actuated, pushes the residue up a ramp, which allows for some drain-back of water. The residue then falls onto a vibrating or belt conveyor. In most plant designs, a single residue conveyor is provided, extending along a bank of several incinerator furnaces. Often, provision is made to insert a chute between the ram discharge and the conveyor to allow the ash to bypass the conveyor and dump on the floor. Ash is then picked up and hauled off using a front-end loader and a small dumpster container or truck. This bypass chute is used to deal with emergencies or for conveyor maintenance.

Since residue removal is critical to continuous operation, drag chain systems, which are susceptible to jamming and other outages, are usually fitted with twin tanks, each with its own conveyor. A deflection plate is used to direct the residue into one or the other quench tank.

3.8.3.2. DUCTS, BOILERS, AND BREECHING

Generally, solids incinerator flue gases contain a high concentration of fly ash. To avoid buildup in ducts, boilers, and breeching, it is appropriate to install hopper bottoms for ash withdrawal. Long horizontal runs should be avoided unless frequent downtime for clean-out is anticipated. Even then, consideration should be given to providing clean-out doors and other means to remove the accumulated solids.

3.8.3.3. RESIDUE PROPERTIES

The residue must be regarded as a source of secondary pollution, or, if nothing else, as a new waste requiring disposal. For many wastes, the residue is enriched in heavy metals (especially fly-ash solids), which may be of significance in establishing acceptable means of ultimate disposal. In recent years, concern has been expressed by environmental and regulatory groups regarding the hazards of ash handling and disposal.

Handling, storage, and transportation practices, as they might affect worker health and safety, and ultimate (landfill) disposal of the ash, as it might impact on groundwater, have been under scrutiny. In some states, regulations have been promulgated to require ash testing, ash planning, and other steps to address concerns that have focused on heavy metals and dioxins.

Residue data are available in the literature (1, 51) and in the appendix.

3.8.4. Pyrolysis and other Gasification Systems

3.8.4.1. EARLY PROCESS DEVELOPMENTS

Earlier in this chapter, the basic concept of pyrolysis was described. This subsection describes the hardware concepts that have been employed to carry out refuse pyrolysis on a commercial scale. In each method to process refuse by pyrolysis, the objective was the same, that is, to convert a heterogeneous, hard-to-handle material into gaseous and liquid fuel products suitable for firing in conventional combustors. Affecting such a fuel conversion step resolves in part a critical step in exploiting refuse energy content to reduce solid waste disposal costs, and thus lead to the marketing of the energy resource.

It may be significant to observe that all of the systems were studied by relatively large, sophisticated firms, each with extensive experience in design and operation of combustion systems and associated air pollution control equipment. Nonetheless, all of the processes, after the investment of years of effort and many millions of dollars in both equipment and manpower, have been shut down. Commercial as well as process failures drove the decisions to cease development, and the failures reflect the especially difficult challenges of handling and processing solid waste while achieving the superior environmental performance demanded of facilities that operate in, near, and for communities.

The problem facing the designer of a system operating in the pyrolysis mode is to find a way to apply heat to refuse sufficient to raise its temperature 4300°C or more without adding oxygen, which will burn the pyrolysis products. This has been accomplished in three ways: (1) indirect heating, (2) zoned partial combustion, and (3) fluid-bed flash pyrolysis. Each of these approaches was studied in the 1960 to 1970 time period, the halcyon years of waste processing process development.

3.8.4.1.1. Indirect Heating Using this approach, refuse is placed inside a metal cylinder that is heated on the outside surface by burning the pyrolysis gases. Such a processing method has been used by Pan American Resources of Albuquerque, New Mexico. Their 40-ton/d unit (the Lantz Converter) uses a rotating kiln design with an airlock seal for the feed. Pyrolysis temperatures range between 480° and 820°C depending on the refuse characteristics. Test work, initiated in 1968 at a Ford Motor Company assembly plant in San Jose, California, was not promising and the operation was discontinued. The Destrugas system, developed in Copenhagen, Denmark, is also reported to use a retort-type, vertically oriented cylindrical system.

3.8.4.1.2. Zoned Partial Combustion In general, pyrolysis systems seek to produce a gaseous product suitable for transmission over some (limited) distance and useful as a fuel in existing boilers or gas turbine combustors. Thus, the char fraction represents a waste product. The zoned partial combustion approach makes use of the heat of combustion of the char to produce a hot gas that, when passed over or through the incoming refuse, produces the thermal environment necessary for pyrolysis. Careful control of the addition of oxidizing gas (air or pure oxygen) limits the combustion to the char fraction, thus maximizing the product gas yield and heating value (kcal/m³).

The Monsanto Landgard© system, constructed during the 1970s in Baltimore, Maryland, with a design capacity of 910 ton/d, was an embodiment of zoned partial combustion using a rotary kiln as the pyrolysis vessel. Fuel oil was burned in the

discharge zone to add additional pyrolysis heat. Excess air (relative to the fuel oil) acted to burn the char. The hot, oxygen-deficient combustion products then passed up the kiln, effecting pyrolysis and feed drying. The Monsanto system encountered severe problems in control and with air pollution. The latter may have been associated with an inadequate design of the scrubber system, although it was suggested that volatilization of salts in the extremely hot char-burning zone may have produced such an abundance of submicron particulate that almost any air pollution control device would have been overwhelmed. In any event, limited combustion capacity, air problems, and other operating problems ultimately led to the shutdown of the operation.

A second type of zoned partial combustion system uses a vertical shaft furnace configuration. Combustion occurs in the lower region of the furnace and the hot gases pass upward through the incoming feed plug. The Union Carbide Purox© system effects combustion with pure oxygen, thus avoiding dilution of the product gas with the nitrogen associated with air-derived oxygen. The Andco Torrax© system uses air for combustion, but preheats the air using a portion of the product gas. These systems were demonstrated at the 100- to 180-ton/d scale, but continuing problems with sidestream treatment (the tarry water condensed from the product gas), maintenance, on-line availability, and capacity led to shutdown of the operations.

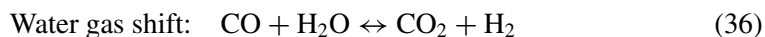
3.8.4.1.3. Flash Pyrolysis The third approach to commercialized pyrolysis processes refuse that has been thoroughly prepared (coarse shredding, drying, air classification, and final shredding of the combustibles to a very fine size), in a fluid bed. Fluidizing gases, preheated by burning the pyrolysis char, rapidly heat the incoming refuse. The rapid heating rate maximizes the yield of liquid products. A 180-ton/d San Diego, California, demonstration plant was tested in the 1970s by its developer, the Garrett Division of Occidental Petroleum. Operating problems and fuel preparation problems ultimately required shutdown of the facility.

3.8.4.2. GASIFICATION

The strong concern of many environmental action groups and of the regulatory community has put the spotlight on air emissions from municipal waste combustors (MWCs) fostering vigorous opposition to proposed plants and to the adoption of increasingly stringent emission requirements. One response in this adversarial environment has been to upgrade the processes and enhance the control technology for “conventional” mass burn and RDF-type MWC systems. An alternative approach is to develop altogether new thermal processing technologies that are inherently low in emissions yet still have the target of accepting the wide range of feedstocks comprising MSW. One such class of new, environmentally benign technologies are those based on the gasification of refuse coupled with intensive cleanup of the product gas prior to its use as a fuel.

In its simplest embodiment, gasification occurs by simple heating of organic material to temperatures of the order of 400° to 600°C, whereupon complex molecules break into shorter chain species that are gases under the extant conditions. This is pyrolysis-type gasification as described above. A second strategy used to effect gasification exposes the organic material to hot steam that heats the material, inducing pyrolysis, and also acts as an oxidant that, via the water gas and water gas shift reactions, yields a gaseous fuel product with minimum char residual and without addition of nitrogen. The key reactions

include the following:



Gasification processes applied to MSW are often (but not exclusively) fed waste previously subjected to recycling and refined to an RDF. The organic fraction is heated with limited or no air to yield a gaseous product stream with substantial heat content. This intermediate product gas can then be cleaned of metals and other particulate matter and of HCl, HF, ammonia, hydrogen sulfide, and other gaseous contaminants. The gas can then be used as a chemical feedstock or can be burned in a gas engine or gas turbine to generate electricity. The gas cleanup effort need only deal with the relatively small quantity of product gas stream from the gasification reactor. This contrasts with the scale of cleanup for conventional incinerator flue gases that have been greatly expanded in volume by the addition of almost twice the theoretical quantity of combustion air and associated high dilution with nitrogen and excess oxygen. As a consequence, the equipment and operating cost for environmental emissions control applied to gasification systems can be substantially lower.

Further, the ultimate combustion process and energy conversion takes place with relatively high-quality, clean fuels comprised, importantly, of CO and H₂ rather than a flue gas derived from MSW and thus bearing corrosive particulate, acid gases, and moisture. Combustion of a “clean gas” allows use of high-efficiency technology for energy conversion (high kWh/BTU) and produces very low emission rates of dioxins, acid gases, and other problematic pollutants.

Gasification is an old technology, with roots in charcoal making, in the reduction of iron and other metal ores, in the manufacture of city gas, and the like. MSW gasification is a more recent application of the technology and, early in the new millennium, is still in the advanced developmental stage with only a few plants, worldwide, based on this technology that have continuous operating experience under commercial conditions. Thus, it is reasonable to expect that process or equipment deficiencies or difficulties will appear in the technologies still under development.

A study of emerging gasification technologies conducted in 1996 identified three that appeared near to commercialization: TPS Termiska AB, Nykoping, Sweden, a process developed by Battelle Laboratories, Columbo, OH, and a process by Thermoselect Inc. Malvern, PA (52). All involve gasification of MSW (Termiska and Battelle with an RDF feed stream and Thermoselect with raw, unprocessed MSW) followed by fuel gas cleanup and gas combustion for the generation of electricity. The descriptions of the processes given below are intended to highlight the technical features and characteristics of these three examples of MSW gasification.

3.8.4.2.1. General The handling of MSW is one of the major challenges to successful implementation of any MSW system. Since heat transfer to the feed waste is a basic step in gasification, almost all gasification technologies require processing of raw MSW to an RDF. The more uniform and highly subdivided character of RDF increases the rate of gasification processes and assists in achieving high conversion efficiency.

Two of the three processes discussed use fluid bed technology. A classical, bubbling fluid bed combustor involves a cylindrical or rectangular chamber containing coarse sand or similar bed material through which gas is passed at a rate that causes the sand bed to expand and move in a turbulent, roiling motion. If the gas velocity is further increased, a fraction of the particles will be blown out of the bed. One can then interpose a medium- to low-efficiency particulate collector such that the larger particles will be captured and returned to the bed for continued processing. Often, an array of vertically oriented steel channels is mounted in the duct leaving the freeboard. These channels (known as “U-beams”) intercept the coarser solids. The U-beams are followed by a somewhat more efficient particulate capture system such as a cyclone that collects 100% of particles with greater than a 30- μm aerodynamic diameter. This embodiment of the suspended combustion concept is called a circulating fluid bed.

The advantages of the fluid bed environment include the uniformity of chemical and temperature environment brought about by the mixing effects and thermal inertia of the dynamic motion of the sand and the effectiveness of the circulating sand both to carry heat to incoming material to dry and to abrade feed particles. The abrasion removes the ash layer that protects the unreacted core material, and reduces the particle size to facilitate combustion.

Product gas can be characterized by its relative heat content class:

Low heat content gas:	950 to 2800 kcal/Nm ³	100 to 300 BTU/sft ³
Medium heat content gas:	2800 to 5700 kcal/Nm ³	300 to 600 BTU/sft ³
High heat content gas:	>5700 kcal/Nm ³	>600 BTU/sft ³

The basic objective of gasification-based processes is to convert a heterogeneous solid fuel with handling and pollutant-emissions problems into a combustible gas containing the maximum remaining heating value. In a way, this is an extension of the RDF preparation to produce a high form value—gaseous fuel. In many cases, the combustible gas is burned in a gas engine or turbine combustor to generate electricity. Where warranted, heat recovery from the exhaust of the engine or turbine can be passed to a boiler to produce steam, and the steam, in turn, is converted to a second quantity of electricity using a conventional steam turbine/generator.

3.8.4.2.2. TPS Termiska Processor—Gasification by Partial Combustion The TPS Termiska Processor (Thermal Processes) is a Swedish firm. The TPS gasifier is composed of a bubbling fluid bed into which RDF or RDF pellets are fed. Secondary air addition partway up the furnace transforms the bed aerodynamic balance such that smaller, lighter particles are blown from the circulating bed. Heavy, still-burning “chunks” remain in the dense bubbling fluid bed until they are consumed. Ground dolomitic lime is added in a second bed to catalyze the breakdown of high molecular weight hydrocarbons into lighter products. The product gas may be cleaned to generate a fuel gas suitable for use in a gas engine or turbine or can be burned directly in a boiler or process furnace. The flowsheet is shown in Figure 10.13.

Extensive development and testing work using MSW and other biomass feed stocks were carried out in the late 1990s. Semi-works scale facilities using the TPS technology were tested using wood biomass in the early years of the new millennium.

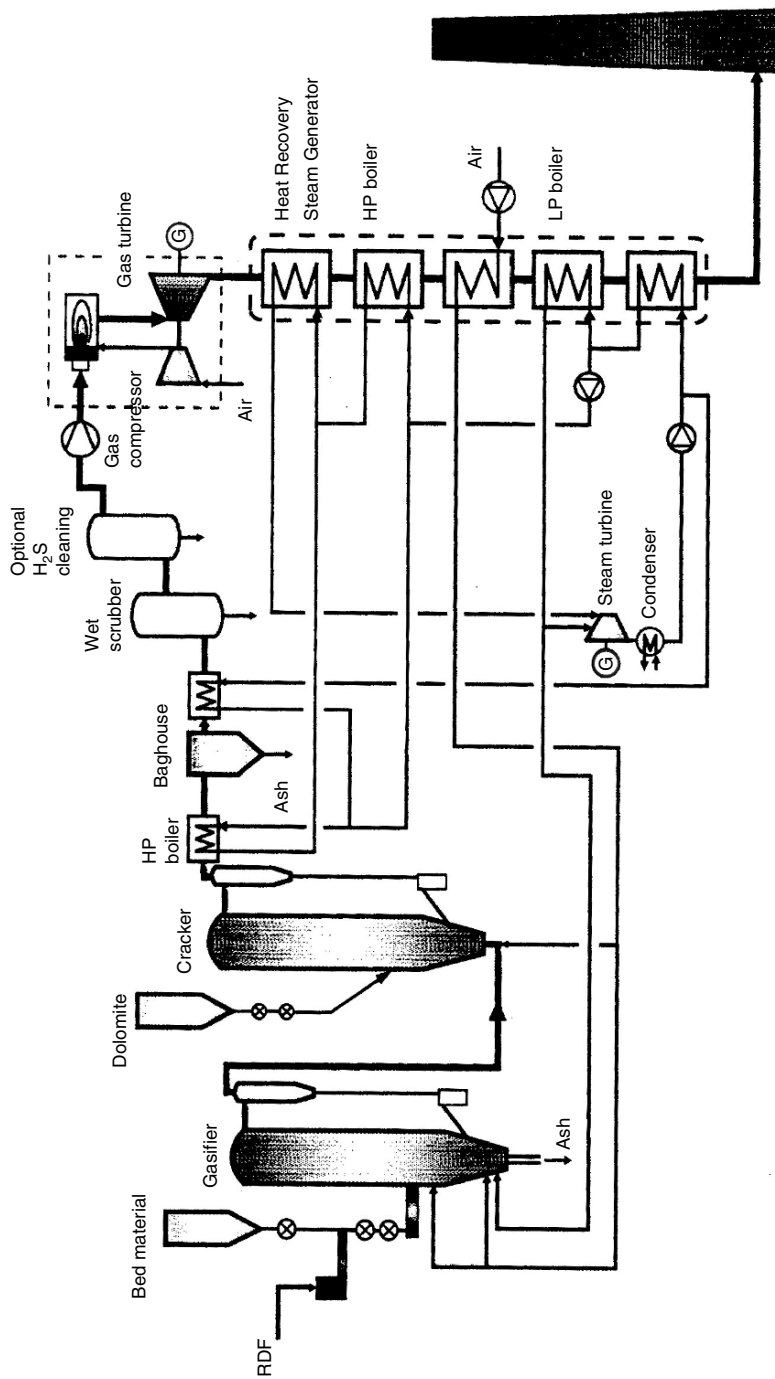


Fig. 10.13. Termiska processor refuse gasification system flowsheet.

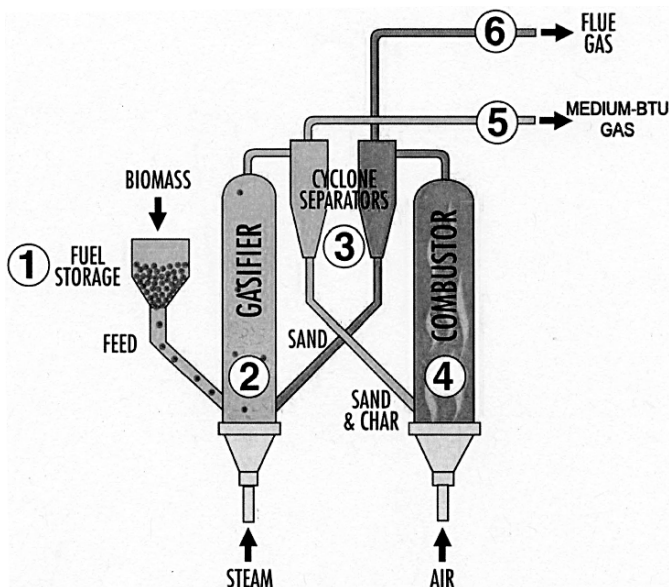


Fig. 10.14. SilvaGas© refuse gasification system flowsheet.

3.8.4.2.3. SilvaGas Process—Gasification by Pyrolysis and Steam Reforming The SilvaGas Process was originally developed by Battelle Memorial Institute of Columbus, Ohio, as the Battelle High Throughput Gasification System (BHTGS). The process uses a pair of interconnected, circulating fluidized bed (CFB) reactors. In a CFB, relatively small particles of solid material are introduced into a fast-moving gas stream. After a few seconds of gas-solid contact time (during which heating, reacting, or oxidation processes occur), the solids are carried out of the chamber and are captured using a simple cyclone device. In the first high-throughput CFB of the BHTGS, refuse-derived fuel (RDF) or other biomass feedstock is gasified to a medium-heating-value gas using steam (without oxygen) as the fluidizing medium and hot sand as the heat source. Residual char and sand collected in the cyclone separator that follows the CFB is burned with air in the second CFB. The sand (now heated by the combustion process) is collected following the second bed and is then circulated back to the first bed as its source of heat. The gasified RDF fuel gas is cleaned and passed to a combustor (a boiler, or a gas engine or gas turbine) from which electrical energy or shaft power can be extracted. The char combustor off-gas is scrubbed and discharged after energy recovery. A schematic of the process is shown in Figure 10.14.

Battelle's development efforts began with laboratory studies and theoretical analysis in 1977. More comprehensive process development activities were begun in 1980 with the construction of 6- and 10-in diameter process research units (PRUs). The PRU investigations continued through the mid-1980s. The PRU tests logged over 22,000 operating hours on a variety of feedstocks. The tests demonstrated the technical feasibility of the gasification process and provided the basis for generating a detailed process conceptual design. Based on this design, capital and operating costs estimates for commercial plants were also prepared. Testing of a highly prepared RDF was conducted in 1989 in a

10-inch inside diameter, 22.7-foot-high gasifier associated with a 40-inch, 11.5-foot-high combustor.

Battelle subsequently licensed its BHTGS for the North American market to Future Energy Resources Corporation (FERCO) in Atlanta, Georgia. The license is presently owned by Silva Gas Corporation, also located in Atlanta, GA. A 25-MW commercial-scale demonstration was carried out at Burlington Electric's McNeil Generating Station in Burlington, Vermont, using whole tree wood chips as the energy source. The Vermont Gasification Project (VGP), capable of processing 500 tons per day of wood chips, demonstrated the commercial scale viability of the technology. The product gas was burned in the existing McNeil boilers. Based on the success of the VGP plant, SilvaGas is currently focused on project development efforts of SilvaGas plant sizes equivalent to 10 to 50 MW in size (200 to 1000 tons per day of feed material). The U.S. Department of Energy and private investors have provided over \$64 million in funding to develop the SilvaGas process.

The various stages of the process are as follows:

- **RDF preparation:** The raw waste is received and stored using conventional floor dump and front-end loader means. In larger plants, pit and crane technology could be used. Waste is then processed using horizontal shaft hammer mills, air separators, and similar conventional RDF processing equipment to produce a 2-inch top-size RDF feed material. The RDF product is then stored in a live-bottom bin that continually recirculates the RDF to avoid felting entanglements that often result in an irregular feed rate.

Typically raw MSW contains many materials such as the residual glass and metals remaining in the waste that do not provide any fuel value for energy recovery. To prepare the MSW for use as a fuel for the SilvaGas process, the glass and metal materials must be removed. After the glass and metals are removed from MSW, the remaining material should meet at least the American Society for Testing Materials (ASTM) classification of RDF-3: shredded fuel derived from MSW processed for the removal of metal, glass, and other entrained inorganic material; particle size of this material is such that 95% by weight passes through a 2-inch-square mesh screen. The resulting fuel to the gasifier is assumed to be 480 tons per day (TPD) on a dry basis (654 TPD wet). Interim storage of the RDF is provided by a live bottom bin or similar device (Figure 10.14, label 1) to act as an accumulator.

- **Gasifier CFB:** The SilvaGas system employs a CFB gasifier to provide high throughputs of biomass material. Superheated steam is used as the fluidizing medium to react with the incoming RDF organic matter. On entering the CFB, the RDF first dries and then is rapidly heated to facilitate reactions between the steam and the RDF organic material to form the product fuel gas (Figure 10.14, label 5). Heat for the endothermic drying, heating and pyrolysis steps is supplied to the reactor by introducing sand that has been heated to 1000°C (1800°F). Fluidizing gases enter the gasifier at a level below the RDF feed entry port and an L-valve sand recycle entry.

The product gas and the sand and char from incompletely consumed RDF organic matter exit at the top of the gasifier at 1500°F and enter gasifier cyclone separator systems (Figure 10.14, label 3). The primary cyclone separates the sand and char from the product gas. The product gas, with a small amount of sand, char and ash is then directed to the secondary cyclone separator to complete the gas cleaning by mechanical dust collection.

- **Char combustor CFB:** Heat necessary for the gasification reactions is provided by using a stream of circulating sand which passes between the gasifier CFB (Figure 10.14, label 2) and a high throughput CFB combustion reactor (Figure 10.14, label 4). A small amount of char is produced as a result of the gasification reactions (typically 20% of the feed material).

The heat of combustion of this char, released in the combustion reactor, provides the energy to reheat the circulating sand.

The combustor, a bubbling fluidized bed with a refractory lining, is designed to minimize heat losses. Sand enters the combustor through a closed chute line from the gasifier cyclone. This line enters through the top of the combustor and extends downward into the fluidized bed. The sand bed is returned to the gasifier from the combustor by an L-valve. The L-valve provides the necessary seal between the combustor and gasifier environments.

- Gas cleanup and cooling

Product gas: The SilvaGas process provides a cooled, clean, 4000 to 5000 kcal/m³ (500- to 600-BTU/sft³ (standard cubic feet)) product gas. The product gas is a mixture of CO and CO₂, H₂, low molecular weight hydrocarbons, and water vapor plus some higher molecular weight “tars” and some uncollected sand and other inorganic particles and vapors. Because the gas is reducing in nature, sulfur compounds in the waste appear as H₂S rather than SO₂. Organic halogens in the waste appear as hydrochloric acid (HCl) and hydrofluoric acid (HF). All of the contaminate materials must be reduced in concentration to meet the environmental requirements of the fuel gas user. These may vary widely, and therefore the technology for gas cleanup is necessarily tailored to the energy market technology.

In general, however, cooling is the first step in gas treatment. Cooling from the CFB discharge temperature of 815°C (1500°F) to approximately 315°C (600°F, 60°F, 1 atm.) provides energy to preheat the combustion air or to warm air with which to pre-dry the RDF stream (dry RDF yields a more efficient conversion of the chemical energy in the waste into product gas fuel value).

The second step in product gas cleanup involves a wet scrubber. The condensed, organic phase scrubbed from the product gas is separated from the water, in which it is insoluble, and injected into the combustor CFB. Also, the wet scrubber would remove much of the particulate matter and, if maintained alkaline, would collect the acid gases H₂S, HCl, and HF. The final gas treatment train, however, has not been settled pending discussions with the ultimate gas user.

Combustor gas: Exhaust gases from the combustor at 1000°C (1800°F) pass through a cyclone separator, which discharges the hot, coarse, separated sand particles directly back into the gasification fluidized bed. The flue gases then are further cleaned and cooled by a waste-heat recovery system before being exhausted to the atmosphere. Waste heat recovery can include the production of steam for the gasification CFB, electrical generation, or turbine drives on the fluidized beds or for RDF drying.

In pilot tests with RDF, the SilvaGas process tests produced gaseous emissions from the char combustor that were in compliance with US EPA’s New Source Performance Standards (NSPS) for MWCs. Wastewater from the process contained only trace quantities of organic materials. At Battelle’s test site, the outlet of a simple, industrial treatment system—a sand filter followed by a simple charcoal filter—showed wastewater to be within US EPA’s drinking water standards.

Chlorine was not measured during the RDF testing. However, subsequent proprietary Battelle data indicate that chlorine in the waste stream is converted completely to HCl in the gasifier and not to chlorinated organic materials such as dioxins and furans. There is a small concentration of HCl present in the gas, most of which is removed by the wet scrubber.

3.8.4.2.4. Thermoselect®: Gasification of Raw MSW by Pyrolysis The Thermoselect process embodies a fully developed method of gasifying MSW without apparent adverse impact on the environment. The residues of the gasification process and the gas cleanup system can be converted into potentially commercially useful by-products such that there is no net waste to landfill. A standard design has been developed around a nominal 400 t/d furnace. Larger facility capacities are offered by adding multiples of the standard

Table 10.18
Typical syngas composition

Average syngas composition	Volume percent
Carbon monoxide (CO)	34–39
Hydrogen (H ₂)	32–35
Carbon dioxide (CO ₂)	22–27
Nitrogen (N ₂)	3–4
Methane (CH ₄)	<0.1
Other	<0.6

Table 10.19
Installations of thermoselect process units

Location	Start year	Capacity mg/day*	Capacity tons/day*
Fondotoce, Italy	1992	1 × 95	1 × 105
Chiba, Japan	1999	2 × 150	2 × 165
Karlsruhe, Germany	2000	3 × 240	3 × 264
Tokushiki Yoshino, Japan	2003	2 × 60	2 × 66
Matsu (Shimokita Area) Japan	2003	2 × 70	2 × 77
Sainokuni City, Japan	2004	2 × 200	2 × 220
Kyokuto, Japan	2005	1 × 95	1 × 105
Kurashiki City, Japan	2005	3 × 185	3 × 203
Isahaya, Japan	2005	3 × 100	3 × 110

* Number of processing modules × capacity/furnace, e.g., 2 × 200 means two furnaces, each of 200 mg/day.

modules. Thermoselect technology is made available in the U.S. through Interstate Waste Technologies of Malvern, Pennsylvania.

The Thermoselect system processes commingled MSW and clean commercial and industrial waste and converts them into what are stated to be environmentally safe and marketable products including a cleaned synthetic gas (syngas), vitrified solid granulates, metal pellets, a zinc salt concentrate, and elemental sulfur. If a full “zero discharge” concept is desired, no net liquid effluents need be discharged into the environment since all process water can be treated and recycled. In addition, the process is intended to minimize the formation or emissions of particulates, nitrogen oxides, and other pollutants.

When a waste feed containing 50% organic matter, 25% organic, and 25% water at 4472 BTU/lb is processed, a syngas of about 224 BTU/ft³ and having the average composition shown in Table 10.18 is produced.

Gasification is achieved at a high temperature. The products of gasification are then held at high temperatures for more than 4 seconds—a relatively long residence time. Data indicate that this combination of time and temperature destroys the complex organic compounds produced in the gasification process and yields a product gas that, substantially, has reached chemical equilibrium. The raw gas is cleaned in an air pollution control/gas purification system, which removes acid gases, hydrogen sulfide, particulates, and volatile heavy metals. Air emissions result only from the combustion of

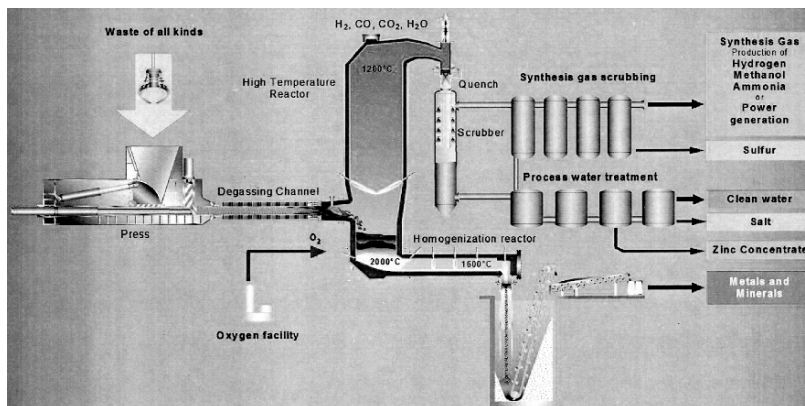


Fig. 10.15. Thermoselect© refuse gasification system flowsheet.

the cleaned syngas in the production of steam in boilers or other means for the generation of electric power.

The original Thermoselect development and demonstration facility was located at Fondotoce, Italy. The equipment consisted of one process line with a nominal capacity of 4.4 t/h, housed in a low-level building with two relatively short stacks. Normal operation was in progress during an inspection visit by Camp Dresser and M-Kee Inc. (CDM) staff in 1966 and included the delivery of municipal and bagged industrial wastes by truck. No odors or noise was observed either inside or outside the plant. Similar operation was noted during a subsequent inspection by CDM of the Karlsruhe, Germany, facility in 2001.

Commercial plants constructed and operating elsewhere are listed in Table 10.19. The third and fourth columns show the number of processing modules and their capacities. Of the nine plants shown, the Karlsruhe and the Fondotoce plants have been shut down. Recently, a project has been proposed for Puerto Rico. Figure 10.15 is a schematic of the Thermoselect gasification system. The various stages of this process are as follows:

- **Compaction:** The raw waste is dropped by grapple from the waste pit into the housing of a compactor that compresses commingled waste to less than 10% of its original volume, thereby removing the trapped air in the original loose material. As the process calls for additional feed, a gate opens and the compactor pushes the plug of waste through an unheated transition section into the degasification channel.
- **Degassing/pyrolysis of the organic fraction of the waste:** The degasification channel is externally heated to a temperature of $600^\circ C$ ($1100^\circ F$). Volatile components in the waste vaporize as the waste moves to the next stage. The heated vapors include steam from water that is evaporated from the solid waste. As the waste plugs are pushed down the degassing channel, they receive radiant heat from the next stage. The temperature in this area approaches $800^\circ C$ ($1470^\circ F$). At this transition point between the degassing channel and the next stage, identified as the high temperature chamber (HTC), the waste plugs have been greatly reduced in physical size due to the loss of volatile components; the nonvolatile organic portion has been to a high degree carbonized; and the inorganic portion of the waste has remained virtually unaffected and is part of the carbon matrix.
- **High-temperature gasification:** In the degasification channel, carbon and water vapor react to form hydrogen and carbon monoxide. These fuel gases move with the other gases into the upper section of the HTC, which is maintained at a temperature of $1200^\circ C$ ($2200^\circ F$). This

high temperature, combined with a residence period approaching 4 seconds and turbulence (provided in this section through a proprietary oxygen introduction technique), destroys any remaining organic compounds. The resulting hot gases exit the HTC and are immediately water quenched in a spray chamber to below 70°C (158°F).

The char and inorganic material fill the lower section of the HTC and, at this point, gaseous oxygen is introduced at a controlled rate. This produces a temperature of 2000°C (3600°F), which melts the inorganic fractions (glass products and various metals) that flow from the lower HTC into the homogenization stage where the melt is prepared for removal from the process.

- Homogenization chamber: The metal and mineral from the HTC enter this stage by gravity. Oxygen is introduced to burn out any remaining carbon particles. To maintain the melt, gas burners may be used. The molten metal and mineral streams are quenched in a water bath. The mineral stream cools and forms a vitrified granulate, and the metal mix freezes as the flow enters the water bath to form metal alloy pellets. The mix of granulate and metal pellets are recovered using a drag chain conveyor. The vitrified mineral granulate meets the US EPA's TCLP (Toxic Characteristic Leaching Procedure) leaching standards.

The vitrified mineral product is not dusty and its metal content remains bound in a glass matrix and does not dissolve in water. This black, glass-like mineral product can be used as the following:

- Raw material components for making clinker brick
- A substitute for cement analogous to the use of anthracite fly-ash
- An additive for concrete
- A filler for bituminous mixtures
- A filler and anti-frost layer in underground engineering
- Mineral fiber and heat insulation fibers
- Decorative pavers and blocks for the building industry

The gaseous environment in the homogenization chamber reduces the metal oxides and causes typical alloy-forming metals such as nickel, chromium, and copper to pass into an iron-rich metal melt. Since this melt has a very low concentration of high vapor pressure components, such as mercury, zinc, cadmium, lead and arsenic, it can be directly used for metallurgical purposes.

The severe duty imposed on the homogenizer section results in a requirement for periodic replacement. The developer includes a spare homogenizer in the basic plant capitalization such that an exchange with a spare section can be performed with minimum line outage. The replacement period is 6 months, and Thermoselect has found that cooling and removal of the spent unit, positioning of the refreshed unit, and restart can be accomplished over a weekend.

- Gas cooling and gas separation from process water: The hot gases in the upper section of the HTC exit are rapidly water quenched to below 70°C (158°F). The syngas and sulfur compounds (present as hydrogen sulfide or H₂S rather than SO₂ because the gases are reducing in nature) are separated from the quench water and passed through successive scrubber stages: an acid wash at 60°C (140°F), desulfurization and a base wash at 40°C (104°F); and finally a cooling state bringing the gas temperature to 4°C (40°F) to remove water vapor. The gases are passed through a coke filter and warmed to ambient temperature prior to use. If appropriate, the syngas can be compressed for distribution and regulation.

The cleaned syngas can serve as an energy source for the production of electricity using diesel engines or as a fuel to a steam boiler. The syngas can also be used as a chemical feed stock to form methanol or benzene. During emergency conditions (as when the energy market is unavailable), the gasifier unit can be shut down. In the coast-down period, the

Thermoselect facility is equipped with an emergency flare chamber to safely burn off the syngas.

The sulfur removal system converts hydrogen sulfide (H_2S) to sulfur using an iron complex via a well-proven, proprietary process. The resulting iron complex is regenerated (52) using oxygen from the air in an adjoining stage.

- By-products of the process: The process water solutions generated from the gas cleaning sections are subject to conventional chemical treatment. Heavy metal hydroxides are removed as a solid concentrate. Elemental sulfur and a concentrate containing heavy metal hydroxides are collected in addition to the syngas, vitrified mineral product, and metal alloy pellets.

The metal and vitrified mineral granulates collected from the homogenization chamber can be density separated when in molten form, but are more easily handled in granulate and metal pellet form, which can then be magnetically separated into vitrified mineral product and metal alloy pellets. The metal pellets consist of iron (>90%), with considerable amounts of copper (3% to 5%), nickel (0.6%), chromium (0.3%), tin (0.4%), and phosphorus (0.1%). Concentrations of heavy metals that find their way into these by-products are at acceptable levels.

The air pollution emissions of the Thermoselect process are uniquely low and essentially are those of a gas turbine burning the CO and hydrogen fuel gas. Thermoselect's goal is for essentially no solid effluents. Thus, the vitreous material is to be sold for use as a fill or concrete aggregate, the metal pellets are to be sold to the scrap metal markets, and the zinc hydroxide concentrate produced in treating the wastewater from the scrubber is to be sold to the zinc recycle market.

3.8.5. *Modular Incineration Systems for Municipal and Commercial Wastes (<100 ton/d)*

In the 1960s, a number of manufacturers, recognizing the increasing emphasis on smoke abatement, began producing incinerators that limited (or starved) the combustion air supply. This design strategy kept flue gas temperatures high and minimized the fuel consumption of afterburner devices. In such units, refuse is charged in batches, and after 10 to 12 hours of charging, the unit is allowed to burn down. Residue is raked out after the burn-down (8 to 12 hours) and the process is repeated. These incinerators are known as modular combustion units (MCUs).

The starved air units consist of a cylindrical or elliptical cross-section primary chamber incorporating underfire air slots in the hearth-type floor. Overfire air is also supplied. The quantity of underfire air is limited to avoid quenching combustion and to minimize the elutriation of particulate matter. The reduced air supply to the primary has a strongly beneficial effect on the entrainment of particulate matter. The slight adverse effect on residue burnout (more carbon char is developed than under fully oxidizing condition) can be resolved in systems where a prolonged burnout period (say, the second and third shifts) is available and, in any event, is not a serious drawback when compared to the significant reduction in particulate emission.

All combustion air is provided by forced draft fans. In many such incinerators, the proportion of underfire to overfire air is regulated from a temperature sensor (thermocouple) in the exhaust flue (higher exit temperatures increase overfire air and decrease underfire air). Most units incorporate a gas- or oil-fired afterburner that is energized whenever the exit gas temperature falls below the set point temperature (usually 650° to

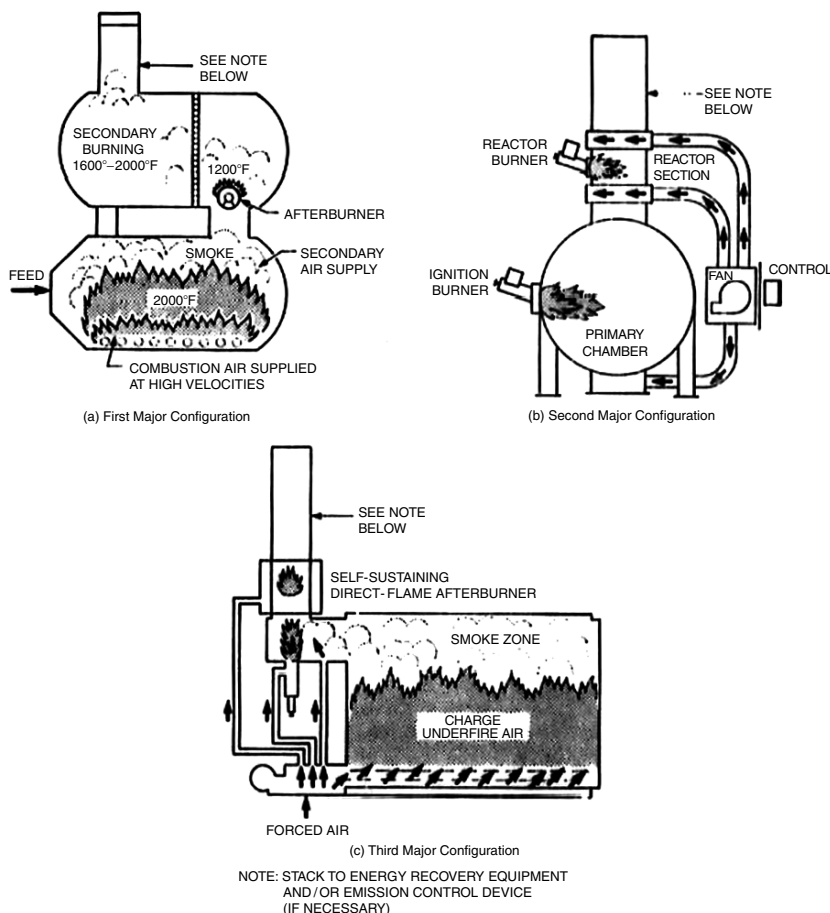


Fig. 10.16. Modular combustion unit (MCU) designs.

750°C). The afterburner is mounted either in a separate, secondary combustion chamber or in a refractory-lined stack. Typical configurations are shown in Figure 10.16.

The MCU incineration systems for solid waste and, in some cases, sludge, liquid, and gaseous wastes are a still evolving product. Many of the major manufacturers of these units entered the market in the 1940s and 1950s when the emergence of the shopping center and the burgeoning growth of packaging stimulated sales of relatively small (45 to 225 kg/h) and simply designed volume reduction aids.

Starved air incinerators are available in capacities from 90 to 900 kg/h (200 to 2000 lb/h) and, for the smaller units and if properly operated and maintained, can meet many federal, state, and local particulate air pollution codes when fed with typical office and plant trash (principally paper, cardboard, and wood). For the larger, municipal scale units, current and more restrictive codes for acid gases and mercury require addition of the conventional dry scrubber and fabric filter system with carbon injection. The modular combustion units can be equipped with a boiler (usually of the fire-tube type) for the recovery of heat. The larger units can also be equipped with automatic feed and

residue removal systems thus increasing the daily throughput and somewhat stabilizing the steam generation rate.

Because of the limited air supply to the primary furnace (about 80% of theoretical), the combustion gases leaving the primary furnace are incompletely burned. The gases leaving the primary contain soot and carbon monoxide, hydrogen, and a mixture of hydrocarbons ranging from methane to tarry aerosols (smoke). Addition of air at approximately 50% excess overall and the use of a small (say, 65,000 kcal/h) burner in the secondary chamber allows combustion to be completed. Because of the operation at low excess air, a higher waste moisture content can be tolerated and energy recovery efficiency is enhanced. The secondary combustion chamber is vital to successful operation and, depending on the throughput of the unit, takes on many forms.

For industrial wastes, vendors of MCUs have developed numerous useful auxiliary equipment including ram loaders, drag chain conveyors for continuous ash removal, and burners suitable for readily pumpable liquid wastes. Generally, the vendor catalogues indicate no change in the hardware configuration between systems to burn the same feed rate of municipal waste (at 2500 kcal/kg) and industrial waste (at, say, 3900 kcal/kg). This inconsistency with normal combustion system experience (where heat release per unit area or volume are key design parameters) suggests that some caution should be exercised when selecting such units. Of particular importance is ensuring that the secondary chamber has sufficient volume to provide adequate retention time at elevated temperatures. This is important for industrial wastes that contain a high concentration of soot-forming materials such as styrene, rubber, or polyethylene. Where no air pollution control is provided, complete burnout of soot and smoke is critical.

The MCU systems have or are being constructed in capacities up to 100 tons per day (24-hour continuous operation). Batteries of the larger units can be installed to serve smaller communities or regions. The facility design is usually simple with a floor dump and refuse storage area serving two or more incinerators. A typical facility cross-section is shown in Figure 10.17. The energy market for these smaller facilities is often steam-oriented rather than electricity.

Field tests by Camp Dresser and McKee, Inc. in a 25 ton per day continuous ash removal MCU showed that the mean residence time of the ash residue in such units is approximately 10 hours. Because of the long residence time, slow drying or slow burning wastes can be incinerated in such units, limited primarily by the overall system heat balance. Such wastes include dewatered sewage sludge and thick-section plastic.

4. THERMAL PROCESSING SYSTEMS FOR BIOSOLIDS

4.1. Introduction

It is an interesting observation that the names of many of the foulest and most detested things, the adjectives that evoke the greatest disgust, the verbs that describe the vilest actions, and the adverbs that shape actions into their darkest forms begin with the letter “s.” It is not surprising, therefore, that the residuum of sewage treatment is one of these “s” words: sludge. The assignment of a negative connotation to sludge is not only related to its origins or its often difficult properties as an engineering material, but to the increasing political, environmental, technical, and economic problems that it presents to

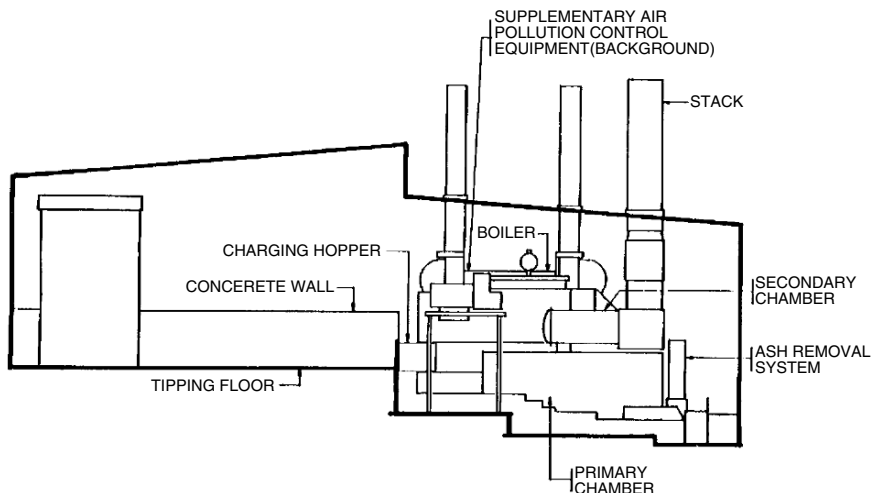


Fig. 10.17. Modular combustion unit (MCU) facility cross section.

the professional biosolids manager. More recently, the noun *sludge* has been changed to *biosolids*, which is not only less offensive but also has broadened in its meaning to incorporate the several other solid and semisolid residuals from wastewater treatment: grit, scum, skimmings, and screenings.

Since the signing of the Water Pollution Control Act in 1961 and its substantial amendments in 1972, the biosolids management community has told the (true but no longer interesting) story of the problems occasioned by the burgeoning quantity of biosolids produced as the level of wastewater treatment has increased. In recent years, say, since 1980, this story has been expanded to include dialogue regarding the growing significance of biosolids quality as it affects its impact on the environment. However, professional biosolids managers now play the lead in a story that is exploding into the headlines and is shouted across council chambers as public and regulatory concern, focused and reinforced by interest groups, impact on the shrinking number of disposal options that are open to the managers.

Most importantly, the public and political clamor is saying “No!” to more and more of the methods traditionally used in biosolids management. In desperation, the old approaches are being refined, updated, and equipped with more elaborate and effective pollution control systems to meet upgraded regulations and public expectations. Further, where landfills are used for ultimate disposal, these elements of the biosolids management system are rapidly approaching class I quality in their sophistication (and cost).

The broad area of thermal processing offers numerous alternatives for the processing of biosolids. Some of the techniques truly constitute disposal in that the total material constituting the original biosolids solids pass into another’s hands. Other techniques reduce volume, increase biological stability, improve landfill structural characteristics, or otherwise aim to mitigate the management problem, but still result in a residue material requiring ultimate disposal.

4.2. Objectives and General Approach

This section reviews biosolids thermal processing technologies from several perspectives in order to assist the biosolids management professional in understanding the breadth of assistance that can be obtained from thermal processing systems—ultimately, an aid in decision making. It covers the full range of concepts from simple (and not-so-simple) drying, through the several types of thermal destruction by pyrolysis and conventional combustion to high-temperature slagging systems.

Each of the techniques is discussed from several standpoints: the process, the controlling thermodynamic principles, operating characteristics, environmental characteristics, a summary features presentation, and a comment on the current state of development. Where the technologies involve basic combustion processes, the principles and analysis methods discussed previously are applicable and are not repeated here.

The process description is brief in cases where the technology is well known and well documented elsewhere. Where useful, references for additional reading are given. The principal content includes the major items of equipment (their function and operating ranges) and the energy and material flows through the system.

The discussion of thermodynamics and combustion focuses on the heat balance for the system and how it is affected by biosolids and system parameters. Parameters of particular interest in this regard are the following:

- Percent solids: Perhaps the most important single parameter characterizing biosolids is the percent solids. In most wastewater treatment literature, percent solids (rather than percent moisture) is the preferred descriptor characterizing the water content of the waste stream. Note that, for biosolids, moisture content is high (say, when compared to conventional solid wastes) and the treatment process involves progressive separation of more and more water. The percent solids focuses on the goal of maximal moisture removal.

For most publicly owned treatment plants (POTWs), the combination of gravity and mechanical dewatering seldom produces better than a 27% solids cake, and therefore the burning of biosolids is more the burning of water than of the organic biomass.

Further, in many plants, the percent solids is allowed to be the dependent variable in the plant with detention times, effluent quality, and almost all other process variables being held to narrow tolerances. From the standpoint of thermal processing systems, this means that the most important process variable is out of control. Clearly, in view of the increases in fuel expense, the increase in environmental impact, and other adverse consequences of uncontrolled swings in operating conditions that are often associated with such a plant operating strategy, the decision to implement a thermal processing system should be the occasion to seriously reevaluate plant wet-end operating priorities. The performance of several classes of dewatering technology are summarized in Table 10.20.

The solids in biosolids fall into two categories: the combustible and the ash. Combustible includes the organic biomass and other organic matter (scum, leaves, etc.) that is oxidized and driven off in the gas phase in the course of combustion processes. In this category are also the (usually) trace amounts of pesticides and other toxic organic compounds. Often, the combustible content is equated to volatile solids (VS), a biosolids characterization variable often reported in the literature. One must be cautious, however, since a portion of the mass associated with lime and ferric hydroxide and some other inorganic biosolids conditioning chemicals is often included in the determination of VS.

The ash component of the biosolids includes the relatively inert inorganic matter associated with the wastewater flow (grit, silt, and sand, etc.) but also includes the insoluble toxic

Table 10.20
Typical biosolids dewatering effectiveness levels

Level	Percent solids
Gravity settling	
Clarifier	0.20–4
Thickener	3–8
Hydrocyclones	3–8
Biosolids drying bed	85+
Mechanical dewatering	
Vacuum filter	14–23
Belt filter	16–34
Filter press	30–45
Centrifuge (conventional)	14–23
Twin-roll nip press	15–25
Centrifuge (high “g”)	23–35

metal compounds that can be important regarding environmental impact. The ash fusion temperature is an important property of the ash. If too low (e.g., due to the presence of ferric phosphate or other fluxes), the ash can melt together into a “clinker” at combustor operating temperatures. Clinker formation can damage the refractory, block passages, and cause other operating and maintenance problems in combustion systems.

The moisture content of biosolids significantly affects thermal processes due to the high latent heat absorption associated with the evaporation of water and the high sensible heat absorbed in raising the temperature of water vapor to combustion temperatures. The heat of evaporation of water at standard atmospheric pressure is about 539 Kcal/kg (970.3 BTU per pound). The heat capacity of water vapor (Kcal/kg-°C, BTU/pound-°F) at ambient temperatures is about 20% higher than that of air and increases rapidly as the temperature increases above ambient (Figure 10.1). Clearly, these thermal loads are important, stealing from the ability of the inherent heat of combustion of the biosolids to meet acceptable combustion temperatures without use of purchased fuel.

- Heat of combustion: The higher heat of combustion of biosolids combustible (4400 to 7200 kcal per dry kg [8000 to 13,000 BTU per dry pound]) is roughly comparable to that of peat. The heat of combustion is somewhat elevated by the presence of excess oils and greases. Often, biosolids heat content is reported in Kcal/kg (Btu/lb) VS but this is not desirable if the VS content varies much from the combustible content due to high calcium or ferric hydroxide content.

The heat of combustion can be estimated from the ultimate chemical analysis of the biosolids using the Boie relationship (drawn from the DuLong equation (see Equation 5)). It should be noted that heat of combustion can be expected to vary over time. Data indicate that digested biosolids fall into the low end of the heat of combustion range and heat treated (e.g., Zimpro thermally conditioned biosolids fall into the high range). Typical values if the higher heating value (HHV) are shown in Table 10.21.

- Sooting (smoking) tendency: Although not an unfailing rule, the tendency of a material to form soot under less-than-optimal combustion conditions appears to be generally related to the ratio between the unbound hydrogen and the carbon content of a material. This ratio is calculated as:

$$\text{Unbound Hydrogen-to-Carbon Ratio} = \frac{\% \text{Hydrogen} - \% \text{Oxygen} / 8}{\% \text{Carbon}} \quad (36)$$

Table 10.21
Typical higher heating values for wastewater treatment solids

Biosolids type	Typical HHV (kcal/kg – dry basis)
Raw primary sludge	5500–7000
Activated (secondary) sludge	4700–5500
Anaerobically digested primary sludge	3050
Raw, primary sludge, FeCl ₃ –lime conditioned	3900
Biological trickling filter solids	4700–5500
Grease and scum	9250
Fine screenings	4300
Ground garbage	4550
High organic grit	2200

Table 10.22
Comparative sooting tendency of waste materials (1)

Waste material	Unbound H-to-C ratio
Mixed paper	0.0065
Softwood	0.0191
Linoleum	0.0625
Polyurethane	0.0641
Polystyrene	0.0913
Waxed paper cartons	0.0927
Polyvinyl chloride	0.1200
Cooking fats, scum	0.1325
Rubber	0.1333
Oils, paints	0.1343
Polyethylene	0.1677

For biosolids, this ratio is about 0.0032, and Table 10.22 shows comparisons with other materials. It can be seen that biosolids are not inherently a smoky burning material. Note, however, that including greases (scum) with the biosolids adds material of considerably greater smoking tendency. Thus “no-problem” systems can acquire emission problems.

- Percent excess air: The exact air quantity to meet the oxidation needs of the biosolids chemistry (two oxygen atoms for each carbon, etc.) is called the theoretical air or stoichiometric air requirement. Numerous combustion texts (e.g., 1) show the method of calculation of this quantity. Air supplied to the system above the stoichiometric amount is called excess air and usually is added (1) as part of air flow used to mix the flue gases (inducing turbulence to ensure that, everywhere, the gases are above the stoichiometric ratio), and (2) to temper combustion temperatures to avoid overheating of the furnace or ash fusion (clinkering).

As the air supplied to a combustion system increases from zero to the stoichiometric point, the temperature of the resulting flue gases increases steadily. This increase reflects the close coupling between the quantity of oxygen supplied and the release of heat. Above the stoichiometric point, the temperature steadily declines reflecting a dilution of the heat (now, theoretically, 100% released) with excess air.

Auxiliary fuel is required if, with air quantities that meet process requirements for mixing and adequate oxidation of combustible gases, the heat of combustion of the biosolids itself

is unable to bring the flue gases above 800°C (1500°F). The fuel adds sufficient heat to evaporate all liquid water and to heat the flue gases to the level ensuring burnout of smoke and odor. Clearly, the more excess air that has been used with the biosolids, the larger the quantity of gas to be heated and the greater the amount of fuel (per ton of biosolids) that is required.

- Energy parameter: The energy parameter (EP) has been shown as a useful variable to combine in a single term the heat and material balance for the combustion of biosolids or other fuels or wastes. The EP is calculated as follows:

$$EP = (1 - S) \times 10^6 / (S)(B)(V) \quad (37)$$

where

S = decimal percent solids;

V = decimal percent volatiles

B = heat of combustion (BTU/lb volatile solids)

The advantage in using the EP instead of, for example, percent solids to correlate thermochemical calculations, is that EP correlations are usually linear, whereas over broad ranges, the percent solids correlations are strongly curved. It can be noted that for a given percent excess air, the EP collapses the heat effects of water evaporation, flue gas heating, and waste-derived energy supply into a single term.

The operating characteristics of interest here include the relative sophistication needed of operators, the sensitivity of the process to upsets upstream in dewatering or other plant operations, sensitivity of facility availability to the quality and frequency of maintenance; energy efficiency, needs for utilities support (especially water supply), and the like.

The primary environmental characteristics involved with thermal systems involve air emissions: opacity, odor, excessive particulate, and air toxics.

The problem of opacity is usually more associated with organic aerosols (e.g., from greases) and finely divided soot particles than with excessive mass emissions. That is due to the high effectiveness of small aerosol or soot particles to scatter light—the fundamental process underlying an appearance of plume opacity. Therefore, the causes of and cures for this type of problem rest more with improving combustion than with upgrading (particulate control oriented) air pollution control systems.

Odor problems reflect a combination of (1) process characteristics that release or generate odorous compounds; (2) deficient control processes (scrubbers, biofilters, combustion environments, etc.); and (3) inadequate plume dispersion (short stacks, low discharge velocity, unfavorable topography, and unfavorable meteorology). Clearly, the distance to residential dwellings, commercial enterprises, or recreational areas is a nontechnical but key aspect affecting the consequences of paying inadequate attention to odor issues.

All of the processes discussed here have the potential to release odors. The odor character is most often a sewage odor (usually sulfide-based odorant chemistry) but may also include odorants from solvents or other chemical families (volatile organic compounds [VOCs]) or amine-based fishy odors generated in low-temperature thermal processing of high-nitrogen compounds that are stripped from the wastewater solids. Burnt odors (often quite offensive odors formed by partial oxidation of proteins at temperatures high enough to support primitive oxidation reactions but too low for full

combustion at, say, 400° to 550°C [750° to 1000°F] or greater) can arise in some dryer operations. Burnt odors often involve ketone chemistry.

For well-mixed combustion systems, control of all of these odor chemistries is readily affected at temperatures over 750°C (1400°F) in the presence of excess oxygen. If scrubbers are selected, conventional hypochlorite or permanganate systems are adequate for sulfides but acidic scrubbers are needed for amines. Scrubber systems show poor to no removal of the partially oxidized organic odorants. Biofilters are suitable for low concentration sulfide odors and many other odor chemistries where organic compounds are present to which biofilter organisms can be “trained.”

Particulate control for most new incinerators is affected with a combination of a Venturi scrubber and a tray scrubber. Older units used the tray scrubber alone with mixed results. Tray scrubbers are quite adequate in attaining the US EPA control technology-based New Source Performance Standard (NSPS) for biosolids incinerators (1.3 pounds of particulate per dry ton burned) but can be ineffective at low pressure drop levels (10 to 15 inches of water) if they must collect submicron particulate enriched with the heavy metals and organics (collectively spoken of as “air toxics”). The US EPA’s research and policy evaluations reassessed the original standards and promulgated special standards based on processing rate and biosolids heavy metal content (an environmental burden standard) in addition to the requirements for stack gas concentrations of (presumably benign) “particulate.” The emission standards for dryer processes are usually drawn from “process weight” regulations that specify limits on the mass emitted per unit mass processed rather than from the US EPA incinerator NSPS codes. If heavy metal emission (air toxics) is high, newer incinerators have turned to wet electrostatic precipitators to reliably provide high levels of control. When organic emissions become problematical, afterburners that ensure combustion temperatures in excess of 875°C are necessary.

The features and problem areas presented by each technology are also discussed. The final section of each technology discussion notes the state of development: Is the process a commercial reality or still an experiment? In many cases, the technology is fully operational in several plants, so this issue is unimportant. Occasionally, however, a word of caution is appropriate. Since most biosolids management systems are implemented by public agencies with public funds where there is considerable political cost for failure and a lack of real compensation for risk taking, this factor can and should assume major significance in technology selection.

4.3. Low-Range (Ambient, 100° C) Drying Processes

Drying processes aim at stabilization of the biosolids by a drastic reduction in moisture content (say, to less than 15%) and at preparation for possible disposal as a product: a low assay (nitrogen, phosphorus, and potassium [NPK] content) fertilizer, a fertilizer base (to be enhanced by addition of high NPK chemicals), or a tilth-enhancing soil amendment. After making the considerable investment in capital and operating cost to upgrade the biosolids, the decision maker must consider seriously the question: What do I have? Is it still a waste? Or a marginal product with characteristics just barely meeting market requirements? Or a salable product that is welcomed in the marketplace and can be sold at a profit to generate a reliable revenue stream to offset production expense?

The product characteristics that affect marketability include the following:

- NPK value (a minimum of 4% available, slow-release nitrogen is preferred)
- Freedom from dustiness and odor in handling and storage
- Limited trash content (plastic bits, cigarette filters)
- Limited contaminants (cadmium or other heavy metals etc.) that limit applicability
- Reliability of supply
- High bulk density (reducing transportation cost)

4.3.1. *Drying Beds*

Since drying is energy intensive and generates a product of limited marketability (i.e., high energy costs could make economically untenable), concepts that use no fuel at all (solar) are of interest. Drying beds are the most widely used method of municipal biosolids dewatering, but only a fraction of these produce a biosolids product greater than 75% solids. However, for small communities in climates with favorable rainfall-to-evaporation characteristics, the process is low cost, simple, and the product is acceptable (on a giveaway basis) to the community or to local farmers.

Sand drying beds are the oldest and most common types of drying bed. The beds are rectangular with vertical sidewalls. Bed dimensions range from 4.5 to 45 m (15 to 150 feet) and include 10 to 23 cm (4 to 9 in) of sand over 20 to 46 cm (8 to 18 in) of graded gravel or crushed stone. Plastic or vitrified clay underdrains slope to a sump. Variations include paved systems with spaced sand-covered drains (smaller than the sand beds but capable of supporting mechanical equipment for biosolids removal and maintenance) and wedge-wire bed systems that show high rates and acceptable maintenance.

In all cases, thickened and sometimes chemically conditioned biosolids are run into the bed and allowed to drain and dry. In dry climates, the biosolids approach 95% solids. Biosolids removal is often performed manually (especially for sand beds), but some plants use mechanical means. The main sidestream from the process is the bed underdrain liquor that is recycled to the adjacent wastewater treatment plant. Since no purchased fuel is used, the process has excellent energy statistics. In most instances, however, the ultimate dewatering level is only to the 60% to 70% solids level. Sand beds are very simple to operate and maintain. Their often-erratic product quality reflects more climatic variation and loading effects than do process variables under operator control.

The primary environmental characteristic of the drying bed is the potential for odor. While the biosolids applied to drying beds are generally anaerobically digested, from time to time offensive odors are emitted. The very nature of the process makes gaining control of an odor episode almost impossible. Dispersal of masking agents or counter-odorant materials is the only mitigating technique that is available.

The clear benefits of the sand bed derive from its simplicity, limited operator attention and energy consumption, and relative insensitivity to changes in biosolids character. The problem areas include the large land requirements, sensitivity to climate (both rainfall and freezing) and, frequently, odor complaints. This latter problem generally mandates the use of digested or chemically stabilized biosolids as the feed. The product is of limited utility (being often dusty and of low bulk density) and is often land filled.

4.3.2. Direct-Fired Systems

Direct fired dryer systems, where the biosolids moisture is driven off by contact with hot combustion gases, represent a major departure from sand beds or similar approaches to biosolids management. Capital investment, operator sophistication, sensitivity of the process to biosolids variation, and other factors now become important. Further, since a direct-fired system directly contacts the biosolids with relatively large volumes of hot gas, a large and significant odor control problem (and cost) must be addressed either by application of odor control equipment or by other means.

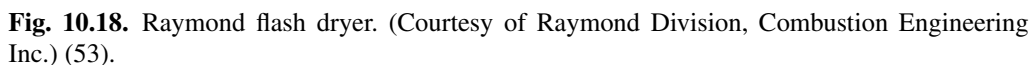
Gases fed to direct dryers at 200° to 300°C (400° to 600°F) emerges with a typical sludge or H₂S-based smell. Experience has shown that this odor is controllable with a conventional hypochlorite-type, chemically oxidizing scrubber. At progressively higher high dryer gas temperatures, the odor character shifts through an intermediate “fishy” smell in the 300° to 400°C (600° to 750°F) range, to a burnt protein smell, which includes numerous pyrolysis-derived or partial combustion products that are not well-controlled with scrubbers; afterburner control devices are required. For energy efficiency, a high-efficiency regenerative afterburner design is preferred. In such units, the incoming cool gas from the dryer is preheated by passing through a bed of hot refractory. Firing fuel raises the temperature of the preheated gas to incineration temperatures of, say, 900°C (1650°F). The burned-out exhaust gases then pass through a second refractory bed, preheating it. From time to time, the gas flow path is switched. Clearly, it is critical that the off-gas is clean enough to avoid plugging of the refractory media.

The two major direct dryer concepts used for biosolids include the flash dryer where a portion of the biosolids (or, if desired or needed, purchased fuel) is burned to generate the hot gases for drying and the rotary pelletizing dryer where burning purchased fuel generates hot gases for drying.

4.3.2.1. FLASH DRYER

Flash-drying is the rapid dewatering of biosolids by direct contact with hot gases. Disintegration of the incoming biosolids to expose surface area and facilitate evaporation is a key feature of this approach. The process was first applied to wastewater biosolids in 1932 at the Chicago Sanitary District. The flash-dryer systems used in the U.S. are primarily those of the Raymond Division of Combustion Engineering Inc. Wellsville, NY. A schematic of the Raymond system is shown in Figure 10.18 (53).

The process is most easily envisioned in three segments. In the first, mechanically dewatered biosolids at, say, 15% to 25% solids is blended to a 60% solids intermediate product by mixing with recycled dry biosolids in a double paddle mixer, pug mill, or similar device. The mixing is carried out to improve the materials handling characteristics for pneumatic transport and, importantly, to “jump” over the 40% to 50% solids range where the biosolids are very sticky and tend to adhere and build up on hot surfaces. The 60% solids blended product is then fed to a cage mill: a fanlike device where the biosolids are mixed with hot furnace gases at 700°C (1300°F). In the cage mill, the biosolids moisture flashes off to produce a 95% solids product that is carried out of the mill by the gas flow. The solids are separated from the gases using a simple large-diameter cyclone device. A portion of the dried biosolids is recycled to the mixer, and the remainder may be either burned to provide the drying heat or drawn off as a product.



The third element of the flash drying system is the effluent gas treatment facility, which includes the deodorizing preheater that accepts cool gas from the cyclone that, through heat exchange with the combustion gases in the furnace, is preheated to about 600°C (1100°F). The deodorized gases leaving the furnace, having attained a minimum temperature of 650°C (1200°F), pass through a combustion air preheater and to a wet scrubber for particulate removal.

Ideally, the leaving gas temperature for the system is 105°C (220°F) to 150°C (300°F) reflecting the energy conservation principles built into the flow system. This results in a net heat rate of 1225 to 1335 kcal/kg (2200 to 2400 BTU/lb) of water evaporated in bringing the product biosolids to about 5% moisture (95% solids). As noted, either fossil

fuels or the biosolids itself can be used as the heat source; the decision as to which fuel to use depends on the marketability of the dried biosolids product and the cost of the fossil fuel.

The flash dryer clearly is a complex flow system with several heat exchangers and numerous materials handling processes. Not surprisingly, these systems are subject to the severe abrasion of the dried biosolids (especially the pug mill and the cyclone metalwork) and fouling of heat exchange surfaces. Materials flow balance can be a problem leading to overflows at, say, the pug mill (a housekeeping problem). Also, plating of sticky biosolids on the cage mill leads to imbalance and bearing problems. The biosolids product made in this device is extremely dusty. This product characteristic creates a potential dust explosion problem in handling, storage, and transport, and detracts from the marketability of the material.

If dried biosolids is not burned as a fuel in the odor incineration system, the environmental problems of the flash dryer are primarily the air emissions from the fuel (SO_2 , NO_x , and, possibly, minor amounts of particulate matter), particulate from the carryover through the cyclone of biosolids solids, and, if the deodorization process is inadequate, odor emissions. The latter should be susceptible to abatement through maintenance of sufficient temperatures in the deodorizing flow stream but at an energy penalty.

If biosolids is burned (in part) as the deodorizing fuel, one can be relatively assured of substantially complete burnout of biosolids organic materials (including trace amounts of pesticides and, most likely, PCBs). However, the combustor operates with a high flame temperature (the combined effects of dry biosolids and preheated air), which suggests potential problems with heavy metal volatilization. Niessen (54) reported that with a flame temperature in excess of 1050°C (1900°F) a large fraction of several heavy metals would vaporize and, without extraordinary efforts at air pollution control (e.g., gas cooling followed by fabric filtration or wet electrostatic precipitation), excessive metal emissions could be experienced.

The primary feature of the flash dryer is the ability to use biosolids energy to provide the drying interchangeably with fossil fuel. Thus, the product stream can be matched to the market; if the market price is high, burn fuel and sell biosolids; if low, burn biosolids and minimize manufacturing cost. As noted in the introduction, however, the dusty nature and inherently low NPK value of flash-dried biosolids reduces the marketability of the product so that careful attention must be given to finding secure markets for the material. Product pelletization after the flash dryer can be considered (with an additional capital and operating cost) to upgrade marketability. The maintenance problems and costs of this dryer concept create operating headaches for the owning organization, and this characteristic should be carefully considered before going forward. The flash dryer system is well-proven technology and is in use in the U.S., Europe, and elsewhere.

4.3.2.2. ROTARY DRYER/PELLETIZER

The biosolids product generated in the flash dryer discussed above and in the indirect dryers discussed below have a significant marketing difficulty: the dustiness of the product. The rotary direct dryer produces a hard particle with limited dust and excellent materials handling and flow properties. In a rotary dryer, wet sludge is fed and hot

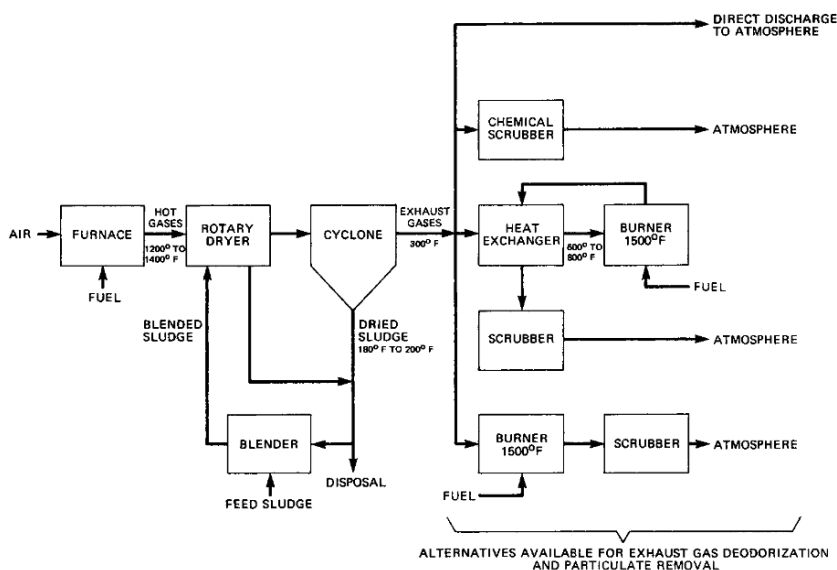


Fig. 10.19. Flowsheet of direct-fired rotary dryer (53).

gases passed either countercurrent or cocurrent. A characteristic of biological sludge is the formation of a sticky consistency at about 40% solids. If this condition forms within the dryer, a “ring” will develop. Thus, the wet sludge from dewatering is always blended with dry material to “jump” over the 40% sticky zone. The sludge is fed, then, at about 50% solids and dried the rest of the way in the dryer. The rotary dryer produces a spherical pelletized product at from 93% to 98% solids, which, using a triple-pass screen, is sized to the 4- to 6-mm-diameter range. Undersize and (crushed) oversize are recycled and blended with the incoming wet sludge cake. A typical flowsheet for a conventional rotary dryer is shown in Figure 10.19 (53).

Single-pass dryers, composed of a single, rotating tube, are more common in Europe. A single-pass design is usually equipped with lifters to elevate and distribute the solids through the gas stream. In the U.S., the triple-pass system composed of three, coaxial tubes is dominant. Flow of the solids in the single-pass configuration is facilitated by sloping the dryer shell (much as is done in a rotary kiln). For the triple-pass concept, the solids are fed to the innermost tube and are moved along by the air stream (thus, only cocurrent flow is possible). At the end of the first traverse, the solids fall to the second tube. The air flow follows and keeps moving the particles along. The process repeats at the end of the second traverse. For the triple-pass system, since the motive action requires operation within a tight range of gas-to-solids relative velocities, the gas flow rate and system dimensions are more narrowly defined and are closely coupled. The multipass system, therefore, is more limited in turn-down than the single-pass unit since a reduction in gas flow may lead to cessation in solid movement through the system.

The selection of inlet gas temperatures is driven by the heat balance on the dryer. First, it must be recognized that a direct dryer system is sized by the gas flow. Second, the evaporative capacity (for a given gas flow) scales directly to the temperature drop of the drying gas between the feed point and the discharge; typically, the discharge is at

about 90°C (190°F). Thus, the capital cost per unit of productivity for the dryer drops as the inlet gas temperature increases. It is the play-off between the fall in dryer capital cost (and an increase in the thermal efficiency) as gas temperatures increases and the increased cost in pollution control (scrubber and afterburner) that sets the design point. Typically, the inlet gas temperature is set in excess of 425°C (800°F).

The rotary pelletizing concept in its several embodiments has become the most attractive alternative in biosolids drying. Particularly in Florida but elsewhere, too, this process is gaining attention as a means to produce a product that can be shipped offsite, not simply sent elsewhere for disposal. Although limited by the inherently low fertilizer value assay of biosolids, the material appears marketable as a soil amendment or for use as a carrier with fortification by chemical fertilizers to a more marketable assay.

A second class of variations in rotary pelletizers concerns the hot gas source and temperature. Conventionally, fossil fuels are direct fired in a furnace with excess air to produce the hot gases for biosolids drying. However, a gas turbine can be used to generate electricity (serving the treatment plant and biosolids dryer complex) with the off-gas (at about 700°C or 1300°F) used for all or a portion of the dryer needs. The gas turbine approach is used in Milwaukee, Wisconsin, in the making of Milorganite, one of the oldest and best known rotary dryer biosolids products. The integration of pelletizing with a gas turbine in Milwaukee's system uses a 650°C (1200°F) gas inlet temperature and would be expected to have odor problems. Their very high stack, which ensures good dispersion under almost all meteorological conditions, provides an important mitigation that enables the system to avoid the use of an afterburner odor control system.

A third concept takes the gases from the dryer, cleans and dehumidifies them in a water scrubber and condenser operation, and recycles them to a heat exchanger where they are reheated indirectly by very hot direct fired furnace gases to produce the medium-temperature dryer feed gas. A bleed stream (only 5% to 10% of the total flow) is drawn off and incinerated for odor control. Air pollution control includes treatment for particulate (usually a Venturi/tray tower scrubber combination) and, importantly, systems for odor control. The latter can include chemically oxidizing systems (chlorine or permanganate-based scrubbers) or thermal oxidation (afterburners).

As with all drying concepts, energy efficiency is vital. For the turbine off-gas systems, heat rates (based on the sensible heat of the turbine gas) range from 830 to 1000 kcal/kg (1500 to 1800 BTU/lb) of water evaporated. Adding an afterburner after the dryer for odor control pushes the upper limit to about 1600 kcal/kg (2900 BTU/lb) of water. If the turbine can be used as an afterburner and the recirculation mode is selected, the overall heat rate drops to 760 kcal/kg (1370 BTU/lb) water. Direct fired systems such as those in Figure 10.19 range from 975 to 1160 kcal/kg (1750 to 2100 BTU/lb) of water without an afterburner and reach 1330 kcal/kg (2400 BTU/lb) with an afterburner.

Rotary dryer systems are relatively easy to operate and maintain. As with the flash dryer, abrasion in the system (dryer body and flights, screw conveyors, and in the pug mill) is the principal area of concern.

The principal environmental concern with rotary pelletizing systems involves odor emissions. As the dryer inlet gas temperature is increased (to increase the dryer evaporative capacity and improve investment capital utilization), the off-gas odor character changes. At inlet temperatures in the 300° to 325°C (400° to 600°F) range, odors are

characteristic of the sewage, that is, sulfide based. As the temperature increases above 325°C (600°F), the biosolids begin to show evidence of thermal cracking and new and more refractory odor chemistry appears, that is, partially oxidized and organic. Unlike the sulfide-based odor, the oxidized materials are not particularly susceptible to hypochlorite scrubbing. Thus, the potential exists to create an odor nuisance. Further, the high political price of creating an odor problem suggests the importance of ensuring positive odor abatement under any conceivable operating condition. This leads to the frequent recommendation for afterburner-like devices for this service. These systems, if designed with heat recuperation features, offer good energy efficiency within themselves and high odor destruction potential, but add significantly to the investment cost.

The primary benefit of the pelletizing dryer concept is the recognizable market for the product. This allows for the potential to recover a portion of the investment made in upgrading the biosolids. The primary disadvantage is the mirror image of the benefit; a system justified on the basis of product revenues may become economically untenable if fuel costs escalate rapidly or if markets become either saturated or constrained (as, for example, through restrictions on pellet use due to health risk concerns relating to the heavy metal content of the biosolids).

The gas recirculation concept is relatively new and creates some potential problems in gas flow control and draft balance. However, with recirculation, the net vent gas stream is very small (5% to 10% of the total), and vigorous odor control concepts (such as an afterburner) become economically acceptable. Full integration of the recirculating system with a turbine (including using the turbine as the afterburner) is as yet untested.

4.3.3. Indirect-Fired Systems

Indirect drying results in greatly reduced odor problems in comparison to those of direct-fired systems. Indirect systems dry the biosolids by contact with hot surfaces within closed chambers. The water vapor is condensed using a barometric condenser. The surface is usually heated by condensing steam but recirculating hot oil is also used. The primary technologies used are the torus disk dryer, the hollow flight dryer, and the tray dryer. Thin-film scraped dryers have been used (e.g., in Dieppe, France) to partially dry thickened sludge from 6% to 8% solids to a product with about 20% solids (i.e., a dewatering function) using “free” steam from an adjacent municipal refuse incinerator, but in the more general case high purchased fuel cost and a limited product dryness range limit the applicability of this approach.

4.3.3.1. PORCUPINE, BEPEX, AND OTHER DRYERS

Several dryer manufacturers have attempted to dry biosolids using steam-heated dryers. In the hollow flight dryer, biosolid feed (usually blended to 50% to 60% solids using a pug mill) is passed through a horizontal steam-heated shell. Steam-heated, hollow blades (such as the cut-flight Bethlehem Porcupine© Bethlehem, PA, dryer or the Komline-Sanderson paddle dryer) move and masticate the drying biosolids and contribute useful heat exchange surface. The Stord© Herlev, Denmark or Bepex© Minneapolis, MN torus disk systems use a shaft fitted with a series of hollow, steam-filled disks that rotate inside a steam-heated shell. A drawing of a Bepex© unit is shown in Figure 10.20.

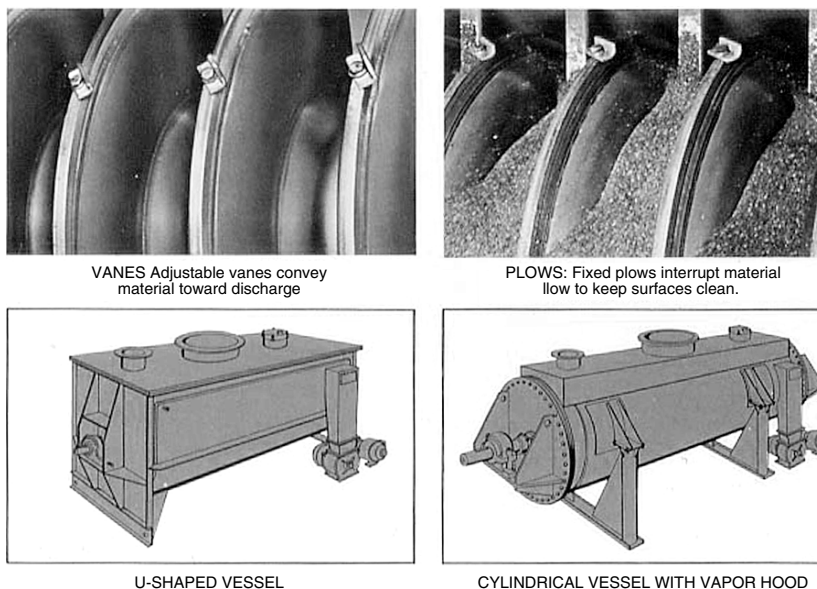


Fig. 10.20. Bepex© biosolids dryer. (Courtesy of Bepex Inc.)

Small metal vanes on the periphery of the disks give a slight but significant directionality to the motion of the material being dried, moving it through the unit. Water vapor (highly odorous and containing both organic oils and ammonia) rising from the drying mass is condensed in a barometric condenser and recycled to the head works of the POTW. All of the technologies mentioned above produce a relatively dusty product at 96% to 98% solids content. Postdryer pelletization is often utilized to reduce dustiness and thereby improve marketability.

4.3.3.2. PELLETECH DRYER

The Pelletech© Baltimore, MD system is a tray dryer configured as a stack of trays mounted inside an insulated cylindrical shell. Each tray is heated with steam or recirculating oil. A central shaft rotates slowly, and arms that project out over the trays plow the biosolids first to the outside wall, where they fall through drop-holes on the periphery to the tray below, and then toward the center, where the biosolids fall through the annular space around the shaft. This device is shown in Figure 10.21. The kneading action of the plows and the drying action on the hot trays act to progressively build a shell on the small dry “seeds” that are part of the feed. This forms the biosolids into 5- to 10-mm spherical pellets. The product is screened on a double-deck screen. The “overs” are crushed and blended with the “unders” for recycle, and the “middlings” comprise the product stream.

Since the principal heat loss from the system is the water vapor at about 120° to 150°C (250° to 300°F), the thermal efficiency of the indirect dryer is high: about 900 kcal/kg (1600 BTU/lb) water evaporated (assuming 80% efficiency in the steam-raising boiler).

Although thermodynamically attractive, the indirect system is often plagued with many of the problems of biosolids drying: abrasion in the dry areas, corrosion from

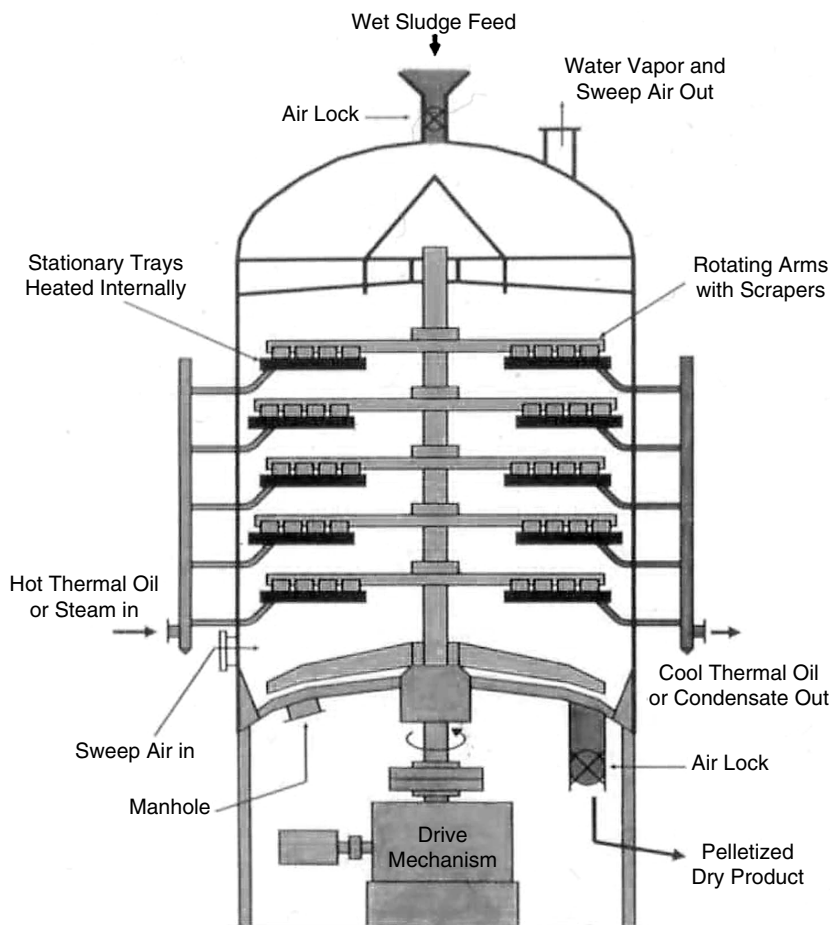


Fig. 10.21. Cross section of Pelletech© biosolids drying system. (Courtesy of Envirogro Inc.)

ferric chloride (if used as a biosolids conditioning aid) in the wet areas, and problems with sticking to the heat exchange surfaces if the biosolids in the unit fall into the tacky 40% to 50% solids range.

From an environmental standpoint, the indirect dryer is potentially superior; there is no emission of pollutant gases, particulate, or heavy metals, and there is inherent containment of odors within the unit. Note, however, that for indirect dryers, a small air flow is maintained through the unit to sweep out the steam (about 10% of the steam weight flow). This steam/air stream is passed to an indirect or direct condenser, and usually the final gas stream (small in volume but highly odorous) is incinerated for odor control. Often, the boiler used to generate the dryer steam can use all of the purged air as combustion air. This economically affects the afterburner function without new capital investment or control-related fuel expense. The off-gas from these units is very offensive, and gas containment and odor control are critical.

Other than the operating problems indicated above, the remaining problems revolve about the marketability of the dried product. Dusty products from the Stord or Bepex technologies do present a marketing problem.

Indirect rotary dryers have had only limited use in the U.S. The Porcupine system in Harrisburg, Pennsylvania, experienced problems with biosolids bonding to the paddle blades (insulating them). The Stord units in Chittenden County, Vermont, and Pittsburgh, Pennsylvania, have had some problems with odor, with buildup of biosolids on the heat transfer surfaces, and with capacity shortfalls.

Sometimes, drying is affected ahead of incineration. The dryer augments mechanical dewatering to reduce or eliminate the fuel requirements for sludge incineration. This application may be seen at the Pittsburgh, Pennsylvania, wastewater plant where steam dryers are used to reduce sludge moisture content ahead of fluidized bed incinerators. Steam is generated “free” by cooling the off-gas from the fluidized bed incinerators. Also, at the Hyperion plant in Los Angeles, the Carver-Greenfield multiple effect evaporation (MEE) process produces a bone-dry sludge powder subsequently incinerated in a two-bed fluid bed incinerator. The first bed is run air starved in a pyrolysis mode and the second bed is fully oxidizing. The City of Youngstown, Ohio, installed a steam dryer to partially dry sludge to eliminate fuel use in incineration.

4.4. Mid-Range (250° to 1000°C or 300° to 1800°F) Combustion Processes

This class of thermal processing includes conventional and several specialized incineration systems. Although capital intensive and incurring high operating cost, incineration offers the advantages of complete destruction of biosolids organic matter, which, in the past, promised easy disposal of the ultimate residue. Recent concerns regarding the leaching of heavy metals from ash make this assumption less confident from the standpoints of permitting and public acceptance.

As the temperature of organic materials is raised, one reaches a temperature above, say 300°C (550°F) where breakdown of the organic chemicals comprising the material is initiated. From the standpoint of heavy metal emissions, limiting the maximum temperature attained by the solids to, say, below 650°C (1200°F) avoids completely the heavy metal emissions, excepting for the special case of mercury and its compounds. Further, if this temperature control is achieved by limiting combustion air (the so-called pyrolysis or starved air mode), fuel use is minimized and essentially no NO_x is formed, and organic or pyritic sulfur in the waste is released as H₂S. Although the off-gas from such a unit needs afterburning, the fuel value of the CO, hydrogen, and hydrocarbons in the furnace off-gas provide a portion of the afterburner energy. Clearly, the afterburning process will produce NO_x and the H₂S oxidizes to SO₂.

Alternatively, one can supply more air and operate throughout in the conventional, fully oxidizing incineration mode. Here, the systems are simpler, and considerably more operating experience exists but secondary problems such as fused clinker formation can arise (since operating temperatures can be high and, for certain biosolids, ash chemistries can exceed the ash fusion temperature). Further, heavy metal volatilization can take place.

4.4.1. General

By far the most common biosolids incinerators (whether pyrolysis or full combustion) are either of the multiple hearth furnace (MHF) or fluidized bed (FB) types. Other than the obvious difference in overall combustion chemistry, the hardware used for pyrolysis

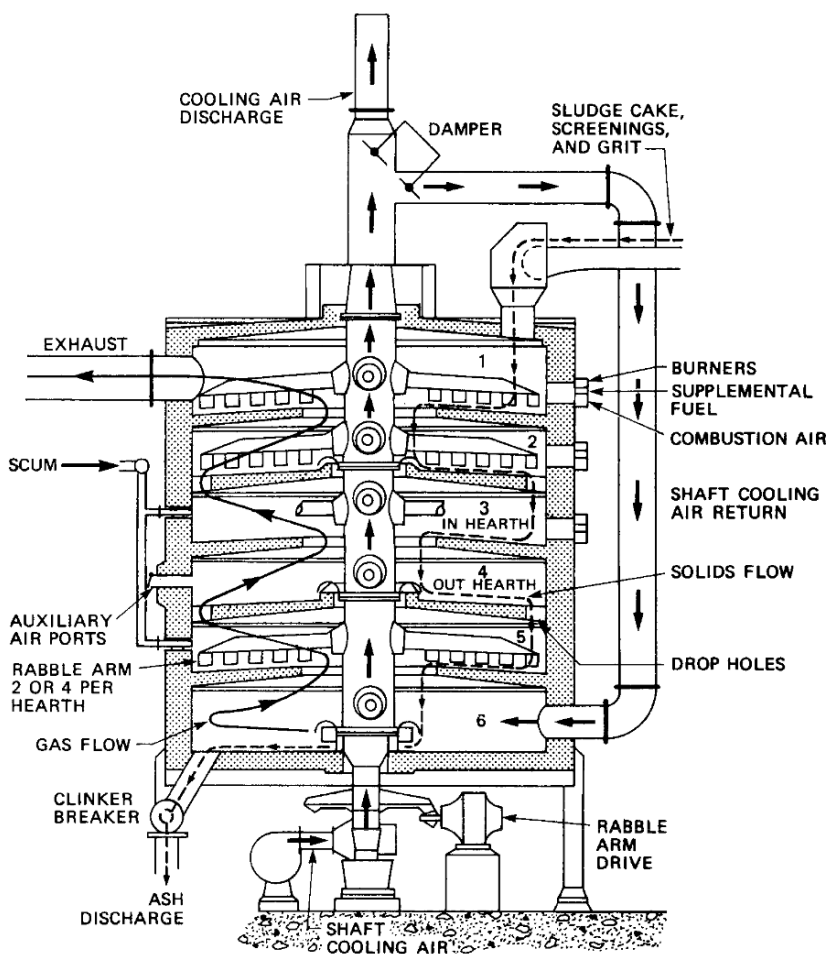


Fig. 10.22. Cross section of multiple hearth biosolids incinerator (53).

or full combustion mode of operation is essentially the same. Thus, for brevity it is appropriate to discuss the hardware for each alternative and then to discuss the specific differences brought about by the operating mode.

4.4.1.1. MULTIPLE HEARTH SYSTEMS

Multiple hearth furnaces (MHFs) are the most common furnaces used for conventional biosolids incineration. By limiting the air supply, they may be operated in the pyrolysis (starved air mode) to give the desirable operating characteristics of pyrolysis within a system well proven in conventional service. Importantly, they also can be configured to switch over to the full combustion mode as a process backup.

The MHF system is designed for continuous operation. Startup and holding energy requirements are too costly and problematic for the equipment to operate intermittently. The system is composed of a stack of from 5 to 11, nearly flat, cylindrical, refractory hearths (Figure 10.22). The hearths are enclosed in a refractory lined shell.

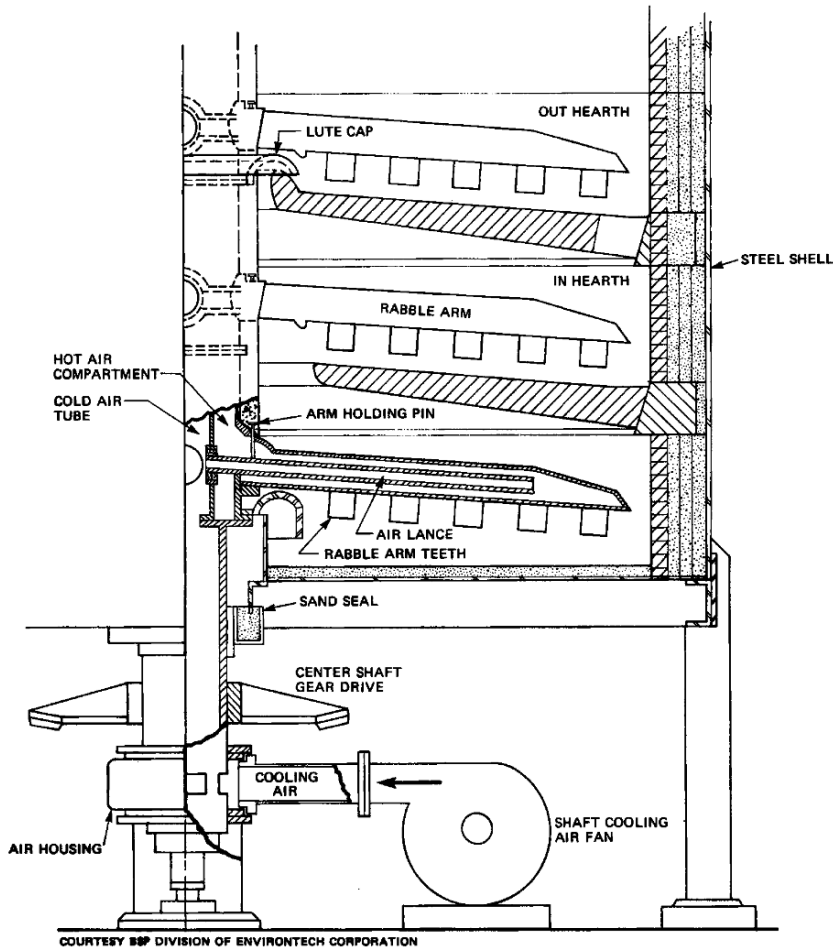


Fig. 10.23. Detail of rabble arm of multiple hearth biosolids furnace. (Courtesy of BSP Div. Envirotech Corp.) (53).

A rotating shaft is mounted in the center of the furnace. The center shaft is equipped with arms that are cantilevered out over each hearth (rabble arms). The refractory clad and air cooled arms (Figure 10.23) (53) are fitted with a series of rectangular plows along their length. The pitch of the plows is adjustable to modify the rate at which the biosolids mass is advanced per rotation of the center shaft.

Biosolids are fed to the outer edge of the top (or, with a bypass, the second) hearth, where it is plowed (rabbed) toward the center, where it drops to the hearth below through the annular space between the hearth and the center shaft. The plows on the second working hearth are pitched in reverse to that on the first hearth, and now rabble the biosolids toward the periphery. Spotted around the periphery are drop holes leading to the next hearth. And the process continues down through the furnace. The rabbling process acts not only to move the material but also to cut, furrow, and open the surface. Indeed, it is estimated that the effective biosolids surface area for drying and combustion is about 130% of the plan area of the hearth.

The upper hearths are drying hearths whereon the incoming biosolids are dried until, at some point, all or a portion of the matter is dry enough to burn/pyrolyze. This heat release from combustion of the biosolids, in combination with energy from burners mounted on most hearths, provides the hot gases used for drying on the upper hearths. The burning process is concluded in two phases: gasification/carbonization and char burnout. Subsequently, the hot ash is cooled with a countercurrent flow of incoming air for heat recovery.

The MHF is a large furnace with considerable thermal inertia. Thus, it can absorb substantial swings in feed biosolids quantity and quality without producing unrecoverable upsets. The behavior of an MHF is complex, with each hearth's processes reflecting the contribution from below of lower hearth off-gases and burners; the contribution from above of biosolids that are in a changing position along the reaction sequence from cold, wet raw feed to ash cooling; and the hearth biosolids' own contribution of heat absorption (drying) or heat release (combustion/pyrolysis), as perturbed by the effects of rabbling speed and burner heat flux and mixing. However, with experience, many operators have learned to bring the units operating in the full combustion mode to a stable condition with a steady and under-control sequence of processes progressing down through the furnace.

The importance of feed stability to satisfactory performance cannot be overstated. Because of the staged character of the MHF process, cycling in feed rate or biosolids percent solids results in the generation of several combustion zones down through the furnace. This can result in the discharge of still-burning biosolids into the residue conveyors with resulting equipment damage. However, with stable feed, the MHF system can be a stable operating system with few operating problems. If the combustion zone temperatures become excessive relative to the biosolids ash fusion point, "clinkers" form as masses of fused ash that can block drop holes and foul or jam the ash conveyor. This problem becomes excessive at temperatures above 1000°C (1800°F).

4.4.1.2. FLUIDIZED BED SYSTEMS

Drawing on the experience in the petroleum and ore processing industries, fluid bed furnaces were introduced to the combustion of sewage biosolids in 1962. Since then, they have seen rapid growth (when fuel was relatively cheap) and severe cutbacks (when, in the late 1970s, fuel costs began to rise rapidly). More recently, the introduction of improved energy-conserving designs, their favorable capital cost, and their favorable environmental characteristics have led to strengthening of their use in biosolids service. The fluid bed (FB) incinerator is well suited to the drying and combustion of a wide variety of biosolids waste. At present, over 85 FB systems are operating in North America and many more in Europe.

Figure 10.24 (53) shows a cross-section of a typical FB installation. The system in Figure 10.24 is designed for high temperature operation such that a refractory arch is indicated as the distribution plate located above the windbox into which combustion air is introduced. Other designs use alloy metal distribution plates. In operation, air at 0.2 to 0.35 bar (3 to 5 psig) is forced into the windbox and passes into the cylindrical furnace through an array of openings (tuyeres) in the distribution plate. Resting on the plate is a mass of graded sand (usually 20 to 80 mesh) from 0.75 to 1 m (2.5 to 3 feet) deep.

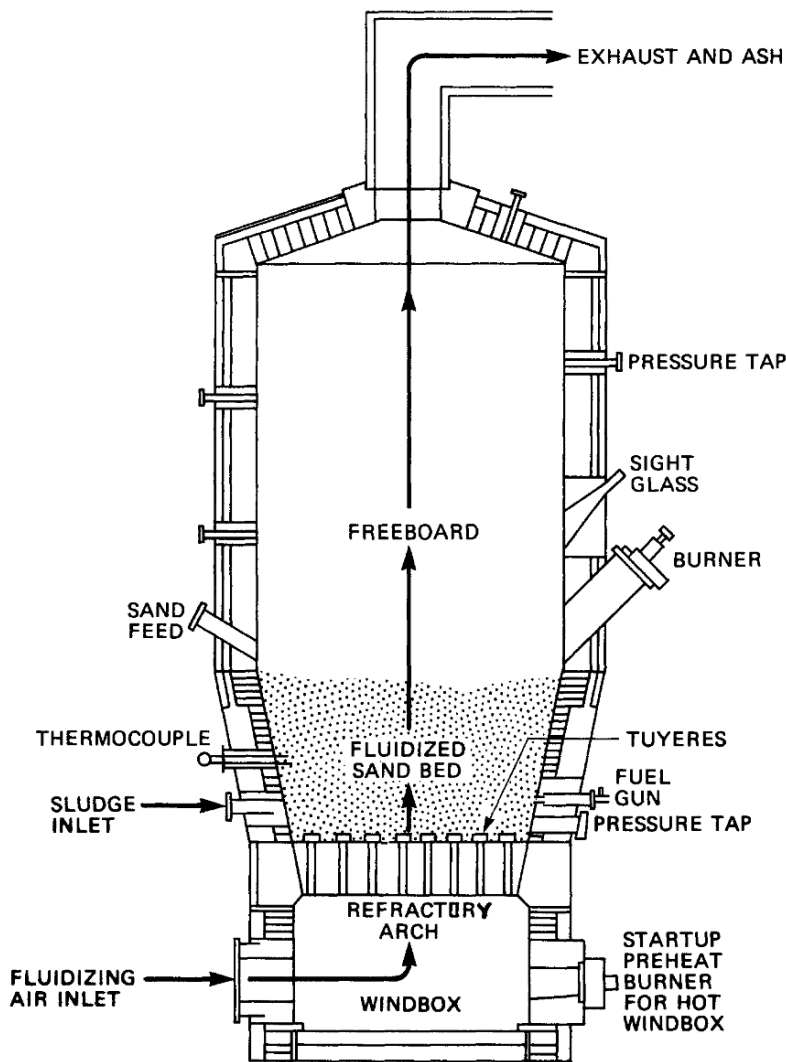


Fig. 10.24. Cross section of fluidized bed biosolids incinerator (53).

The tuyeres are designed to pass air into the bed but inhibit sand from draining into the windbox.

As the rate of air flow increases, the sand bed expands to about twice its original volume—sufficient growth to expand the bed to a working density high enough that the biosolids will not float to the top of the bed, yet insufficient air flow to blow the sand out of the reactor. Typically, the superficial air velocity at the bottom of the bed (based on the bed diameter) is 0.5 to 1 m/s (1.5 to 3 ft/s). The sand in the bed is in a state of violent recirculating motion that maintains a remarkable degree of uniformity in bed temperature. The large mass of the sand, heated to bed temperature, provides a large thermal flywheel effect that protects against rapid fluctuations in bed temperature

if the feed rate or net heating value changes. For example, a 4.5-m (15-foot) diameter freeboard FB reactor, during normal operation, contains about 2 million kcal (8.5 million BTU) in the bed.

Other than the bed itself, key equipment includes the following:

- The fluidizing air turbine blower servicing air to the system
- The freeboard zone (above the bed) wherein combustion is completed; sometimes overfire air jets are mounted in the freeboard to assist the radial mixing process
- An (optional) heat exchanger mounted after the freeboard to preheat fluidizing air counter-current to the hot gases leaving the furnace
- The APC equipment, which can include the Venturi scrubbers common in the U.S. or electrostatic precipitators common in Europe and Canada

4.4.2. Pyrolysis Mode Systems

4.4.2.1. MULTIPLE HEARTH SYSTEMS

In conventional MHFs, the system is allowed to operate with full burning. Thus, the gases leaving the furnace are primarily carbon dioxide, water vapor, and the nitrogen and oxygen from the air. In the pyrolysis mode, with a deficiency of air relative to the stoichiometric requirement, the off-gas contains a spectrum of hydrocarbons, hydrogen, and considerable carbon monoxide. Thus, in the pyrolysis system, a second afterburner chamber is required wherein a burner is mounted (to ensure ignition), and additional air (to, perhaps, 40% excess overall) is added. In some configurations, the “afterburner” function is accomplished on the top hearth and the furnace is configured to bypass the top hearth with the sludge feed. This so-called zero hearth afterburner is simpler in design and lower in cost than configurations using a second chamber as the afterburner. However, the difficulty in achieving good mixing and reliable energy exchange from an afterburner burner to the incompletely burned furnace gases often leads to higher than desired emissions of carbon monoxide, hydrocarbons, and odorous organic compounds.

In the starved air mode, perhaps 80% of theoretical air is supplied to the pyrolysis zones of the furnace. This releases approximately 80% of the heat of combustion in the biosolids. About 5% of the biosolids fuel value can be lost in unburned carbon char in the ash unless the lower hearths are operated above the stoichiometric level to ensure burnout. Looking at the furnace as a whole (including the air addition in the afterburner), the system operates at a net of about 40% excess air. This is in comparison with a conventional MHF system that uses 100% to 150% excess. Since most biosolids incinerators are energy deficient (biosolids energy is insufficient to dry the biosolids), the saving in fuel by reducing air use can be substantial.

Pyrolysis reactions of biosolid organic matter begin at about 200°C (400°F). Generally, pyrolysis reactions are initiated not by indirect heating but by careful air control (the starved air approach) such that the partial combustion of the biosolids material provides the energy for pyrolysis. Although not rigorous, the degree of pyrolysis that is affected at a given temperature T (°C) may be roughly estimated by:

$$\text{Fraction pyrolyzed} = 1.0663 \left(1 - \exp \left[\frac{(200 - T)}{360} \right] \right) \quad (38)$$

The products of pyrolysis range broadly and include simple, low molecular weight hydrocarbons, complex polyaromatics, and a wide variety of partially oxidized alcohols, aldehydes, ketones, and the like. Higher temperatures favor the simpler, low molecular weight compounds, and lower temperatures favor the tarry, heavy oils. Importantly, however, the process involves gasification; the solid organic matter has been moved to the gas phase where combustion can be readily affected and the mixing processes of fuel vapors with oxygen are under the control of the designer. Further, because the temperatures where pyrolysis occurs are several hundred degrees lower than for full combustion conditions, heavy metals remain in the ash. Low emissions are also favored by the low gas velocities (discouraging entrainment) occasioned by the small air flow needed for partial combustion.

In the pyrolysis mode, there is considerably less experience than in the full combustion mode. Data from the Contra Costa County California plant (55) and from extensive US EPA-sponsored pilot plant studies (56) at Nichols' Research and Engineering (Bell Meade, New Jersey) suggest that the pyrolysis mode is easy to control, free of the clinkers that can form under full combustion conditions if hearth temperatures rise to levels much above 950°C (1750°F).

There are insufficient data to authoritatively document the environmental implications of operating in the starved air mode. However, the limited data available suggests lower particulate emissions, good control of hydrocarbon emissions in the afterburner, and considerably reduced heavy metal enrichment of the particulate. It is speculated that the reducing condition in the furnace inhibits the oxidation of chromium from the relatively nontoxic +3 form to the toxic and carcinogenic +6 form. This can be a significant environmental problem that is observed in fully combusting systems when burning high-chromium biosolids sometimes found in communities with substantial metal plating or leather tanning operations.

The primary beneficial features of the MHF system in the starved air mode relate to energy conservation where the lower excess air operation significantly (20% to 40% overall) significantly reduces fuel use. Clinker problems are reduced to a minimum, and it would be anticipated that refractory maintenance would be reduced due to the less severe operating temperatures.

Pyrolysis mode MHF operation is a combination of equipment configuration and operating methodology. The equipment for starved air mode is essentially the same as for conventional MHF operation and is well proven in biosolids incineration service. However, other than the limited Contra Costa and Nichols work mentioned above, there are only limited data on the pyrolysis operating configuration. Two plants (Alexandria, Virginia, and Cranston, Rhode Island) were originally constructed to operate in the pyrolysis mode but have not. Several other plants were run in starved air mode for a short time when "hot" Zimpro conditioned biosolids were being processed and temperatures became excessive.

Unfortunately, many owners and operators of MHF systems have a concern (although not realized in the limited operational experience with biosolids nor in the hundreds of MHF furnaces used for activated charcoal manufacture) about explosions if furnace doors are inadvertently opened when the furnace volume is filled with (combustible) pyrolysis gases. No such events were experienced in any of the furnace tests at Contra

Costa or Nichols. Nonetheless, the absence of a substantial body of working experience requires one to consider the pyrolysis mode as experimental. As noted above, however, it is fortunate that these systems can be readily designed with both conventional and starved air mode capability such that an inherent process backup exists so that experimentation is not costly.

4.4.2.2. FLUIDIZED BED SYSTEMS

As with the MHF, the predominant application of fluid bed furnaces has been in the fully oxidizing mode. However, in the general case, the operation of FB units under sub-stoichiometric conditions is not without experience. Such conditions are used for the fluid bed processing of iron ores, for iron reduction, and for activated carbon regeneration. Installations at the Hyperion POTW in California showed some interesting applications of pyrolysis mode: a three-step, starved air system. The bed was operated at 30% theoretical air receiving a dried sludge from the Carver-Greenfield multiple effect evaporator technology. Published data on the Hyperion plant performance have been limited. However, it is reported that the performance of the FB portion of the plant was very satisfactory. It should be noted, however, with the fully dried biosolids feed, that the Hyperion FB behavior may be atypical. At Hyperion, pneumatic feeder problems were noted with the dry (>95% solids) feed. Air was added from sidewall jets just above the sand bed so that the freeboard operated at 80% theoretical air. The first (of two) afterburners operated under stoichiometric conditions. This was followed by a fully combusting afterburner with, overall, 135% theoretical air at the stack.

With steady biosolids flow, the excellent mixing in the fluid bed unit is indeed conducive to the attainment of a uniform product gas with hydrogen and carbon monoxide (plus small quantities of low molecular weight hydrocarbons) being the predominant forms of unreleased fuel value. The secondary (afterburner) chamber can involve high turbulence with air jets and chamber design combining to ensure complete burnout. In the case of the Hyperion plant, an intermediate boiler was installed to withdraw heat before completing combustion. Intermediate cooling at the stoichiometric point limited NO_x formation (from oxidation of biosolids nitrogenous matter as well as thermal NO_x). Also, the reducing environment would be expected to minimize chromium oxidation.

With conventional biosolids incineration, overall excess air for the process can be limited to about 25% thus reducing fuel requirements somewhat in comparison to fuel use with conventional 40 + % excess air fully oxidizing fluid bed operations. Note, however, that the environmental and operational benefits indicated above are obtained at a significant increase in capital investment and the slightly lower excess air levels allow only a limited recovery of cost due to lower fuel requirements. Problem areas in maintenance are uncertain since so little data is available.

4.4.3. Full Combustion Mode Systems

Full combustion systems are the most common, and their operating characteristics and design features are presented elsewhere (1, 53). In this operational mode, sufficient air is supplied to meet and generally exceed stoichiometric requirements such that temperatures exceed 800°C (1500°F) in most cases.

4.4.3.1. MULTIPLE HEARTH SYSTEMS

The MHF system, operated in the full combustion mode, is the most common means of biosolids incineration in use today. Although not without its problems, the system has shown itself capable of responding to wide variations in feed rate and biosolids characteristics and to provide the flexibility to adapt to seasonal changes and industrialization.

The design features of the MHF system for the full combustion mode are essentially identical to those of the pyrolysis mode. Since combustion of gasified combustible is ideally completed within the unit, a separate afterburner is not provided. However, when biosolids with high grease content are burned, there is often excessive smoking and hydrocarbon carryover. When this problem is anticipated, the system is often configured to bypass the top (renamed the zeroth) hearth, which is then strongly fired with fuel to provide an afterburner function that is relatively inefficient. Retrofit of existing units with a hydrocarbon emission problem is also practiced with this reconfiguration, although usually with a loss in processing capacity.

The key process feature of the MHF is the regenerative aspect wherein the wet, incoming biosolids are dried on the top hearths and then pass through three oxidation zones followed by ash cooling. After drying, the biosolids temperature increases until, in the first of the three zones, thermal breakdown (pyrolysis) takes place with ignition and burning of the pyrolysis gases above the surface. Heat transfer to the dry solids is partially convective (from the hot gases rising from the fully burning zones below), combined with radiation from the hot refractory walls, roof, and pyrolysis flame. The second oxidation zone involves conventional oxidation of biosolids on the hearth. Because diffusion of oxygen from the gas phase to the burning mass is slow, a substantial fraction of the biosolids' organic matter remains as a high-carbon char. The char oxidizes slowly in the third combustion zone. Since there is essentially no liquid water to moderate the temperature, the solids often approach 1000°C (1800°F) in this zone. Finally, cooling of the mineral ash residue takes place on the lowest hearths. Typical temperature levels corresponding to this chain of processes are shown in Table 10.23.

The MHF systems are commonly operated at more than 100% excess air; levels as high as 200% excess are not uncommon. Ideally, a well-operated furnace can operate successfully at, say, 75% excess air, although stable feed composition and rate are essential to achieve these levels. With a stable feed rate (a risky assumption for many plants), the hearth-to-hearth temperatures hold steady hour after hour and, with trim of the system using the variable center shaft speed control, excellent ash burnout and heat recovery from the ash are achieved.

To fully realize the energy economy of the regenerative operating mode, the top hearth temperature gas must be allowed to fall considerably below levels where combustion

Table 10.23
Temperature distribution in MHF systems

	Drying zone	Pyrolysis/burning zone	Cooling zone
Biosolids	70°C	730°C+	200°C
Flue gases	425°C+	830°C+	175°C+

takes place 350°C (650°F). If the biosolids contains large amounts of grease, this may lead to aerosol formation. These grease aerosols may crack or partially burn, leading to emission of fine particle carbonaceous soot (opacity) and odor. Also, raw biosolids can be carried off by entrainment in the gas flow rising through the drop holes. Heavy metal enrichment of the hard-to-collect fine particle fraction may also be a problem if the char combustion hearth temperatures exceed 900°C (1650°F), a condition that is not uncommon.

Several states require that gases in contact with raw biosolids must be reheated. For example, New Jersey requires reheat of the gases leaving the top hearth to 815°C (1500°F). Such a reheat requirement totally loses the regenerative mode advantage, and fuel use becomes comparable to plug flow fluid bed units but without the potential for “energy recycling” with the hot windbox design recuperative mode.

Perhaps the greatest benefit of the MHF is its energy economy (when environmental regulations permit). Also, the inherent inertia of the system provides a flywheel effect that is tolerant of fluctuations in the character of the feed. The problems of the system, aside from the environmental emissions and clinkering problems noted above, result from the considerable complexity and structural frailty of the design. The complexity requires considerable operator skill, and often results in the simple expedient of turning up the air supply to wash out the need for deft operating style and paying close attention to process changes. Clearly, overuse of air greatly increases fuel use per unit mass processed. The structural problem arises due to the flatness of the hearths such that careful control over the rate of temperature rise and fall must be observed to avoid catastrophic hearth failures.

4.4.3.2. FLUIDIZED BED SYSTEMS

Although its application has been dwarfed by MHF installations, the economic and performance advantages of the fluid bed system have made it the dominant choice in new installations. This reflects the greater degree of control available with fluid beds, superior energy economy (with the hot windbox design concept discussed below), and improved air emissions.

The process description of the full combustion mode fluid bed is identical to the pyrolysis mode. The only difference is the proportions of combustible matter and air. Feed systems involve screw or diaphragm pumps discharging into either the bed or dropping through the freeboard. For large furnaces, a “flinger” (a rotating metal vane much like the mechanical spreader stoker discussed for burning RDF from municipal solid waste) mounted at the top of the bed (which is maintained with the draft in balance with atmospheric pressure) can be used to improve distribution.

Ideally, combustion of biosolids organic matter is completed within the sand bed such that a maximum of energy from biosolids combustion is available to dry the incoming biosolids. With high grease-content biosolids or when the biosolids is dropped through the freeboard space, a fraction of the burning takes place in the freeboard. This can starve the bed for drying energy and may lead to overheating (slag formation and buildup) in the freeboard and outlet flues.

The FB biosolids incineration at 750°C (1400°F) and 40% excess air is autogenous at an energy parameter of 225 to 250. As the feed becomes “hotter” (lower EP), the

temperature will rise. The maximum bed temperature is set partially by materials of construction, design features (especially the ability of a refractory air distribution plate to accommodate the thermal expansion or, for alloy metal plates, to survive at the working temperature), and the desire to keep the bed cool enough to both prevent stickiness (incipient fusion) of the sand (rapidly leading to bed defluidization) or excessive volatilization of heavy metals. Bed temperatures at or below 875°C (1600°F) are common.

To improve energy economy, almost all recent designs include a combustion air preheater. In this design, air from the combustion air blower is passed on the shell side of a stainless steel shell and tube heat exchanger to preheat it prior to introduction to the windbox—the “hot windbox” design concept. Flue gases from the furnace are passed through the tube side. With proper distribution plate design (to accommodate the large thermal expansion from the cold state), this technique allows preheating of combustion air to as high as 650°C (1200°F). The combination of modern mechanical biosolids dewatering (to, say, 28% solids) and these levels of air preheat allows essentially auto-genous operation (no fuel use).

Because of the good biosolids burnout affected by the FB, boilers can be added to recover heat from the furnace off-gases without undue risk of fouling. In some plants, boilers are used in addition to the hot windbox design to bring the gases to approximately 250°C (500°F), where they can be passed to an electrostatic precipitator for particulate control. Steam can be used with a turbine drive to reduce electrical costs for the large, high-horsepower combustion air blower as well as for building heat and process hot water.

The FB furnace is stable in operation with, commonly, oxygen instrumentation adjusting the fuel feed to maintain a relatively constant excess air level. Because of the simple refractory design, furnace maintenance costs are low. Maintenance problems with the hot windbox design have been experienced from thermal stresses in the expansion joints of the heat exchanger and some fouling can occur. In general, however, these problems can be dealt with by proper design and operation. One should note in this regard that the on-line availability of the biosolids incinerator is dependent on the availability of the heat exchanger (the most vulnerable part of the system), so prudent vendor and equipment selection has a particularly good payoff.

A unique feature of the FB system, brought about by the high sensible heat content (thermal inertia) of the sand bed and the simple mechanical design, is the ability of the systems to be rapidly shut down (simply turn off the air and the biosolids supply) and held without significant heat loss for extended periods. Thus, a system can be shut down for as much as a day or two and brought back into service in less than a half-hour.

Because of the excellent mixing in the bed and the long residence times of gases in the freeboard, organic emissions from the FB are small. If volatiles do become a problem, addition of air jets in the freeboard is often effective in realizing acceptable burnout of gas phase pollutants. The low bed temperature of the FB allows the operator to avoid excessive heavy metal volatilization.

Although most U.S. systems utilize a Venturi followed by a perforated tray scrubber system, many European plants, in combination with energy recovery in a boiler, use an electrostatic precipitator for particulate control. Excellent particulate resistivity

properties lead to ESP collection efficiency that meets or exceeds U.S. standards. When heavy metals are a concern, several U.S. plants have installed wet electrostatic precipitators with excellent heavy metal collection performance.

The FB units offer a broad range of economic and performance benefits in comparison to MHF systems: simplicity of construction and operation, lower first and operating cost, the potential for energy recovery, and superior environmental emissions. The ability to shut down and restart (say, over a weekend) is also advantageous for smaller POTWs with modest biosolids incineration requirements. The fluid bed, either with a cold or hot windbox, and with energy recovery, is well developed and commercially available from several firms.

4.4.3.3. INFRARED SYSTEMS

The first electric furnace (infrared) furnace was installed in Richardson, Texas, in 1975. Since then, only a few units (less than 10) have been installed for biosolids incineration, importantly due to equipment problems and high electricity cost. The electric furnace system is composed of a horizontal woven stainless steel endless belt that is drawn through a long, refractory-lined chamber. Biosolids are fed and leveled onto one end of the belt and move down the furnace. Electrically heated glow-bars radiate heat to dry and heat the biosolid mass until it bursts into flame. The hot combustion gases pass countercurrent to the entering biosolids to assist in the drying process. Due to the formation of an insulating crust on the top of the biosolids cake, breaker bars are positioned at intervals along the belt to disrupt the crust and expose new surface. Ash is discharged from the end of the belt to an ash-handling system. Combustion air is introduced at the ash discharge end.

The combustion air rate for the electric furnace ranges from 20% to 70% excess, thus offering reasonable thermal efficiency from that point of view. Electrical heating requirements are similar to that of the MHF, but typically the cost of energy as electricity is considerably higher than when it is obtained by burning fossil fuels. When the biosolids are autogenous (e.g., as for some Zimpro biosolids), the energy economy of the electric furnace is superior to the MHF.

The electric furnace operating problems relate, importantly, to the highly mechanical nature of the device. Belt and glow-bar replacement have been costly and outages may be frequent and prolonged. However, the attractive capital cost and modular construction makes the electric furnace potentially attractive for small treatment plant systems with biosolids disposal problems.

The nature of the electric furnace process has shown excessive hydrocarbon and CO emissions. This comes from the poor mixing and stratification within the furnace. In states such as New Jersey, the high fuel costs associated with the state's requirement for an afterburner eliminate the other energy or capital advantages of the electric furnace system. Although data are not available, one could anticipate that excessive heavy metal volatilization may occur in the combustion zone.

The primary benefit of the electric furnace arises from its low capital cost. In general, system operational problems and high energy costs greatly overshadow this benefit. The electric furnace is still in the advanced state of development. Limited sales and experience in biosolids management service has not supported extensive experimentation

to optimize the configuration of air systems, glowbar design, belt materials, and support/drive concepts.

4.5. High-Range ($>1100^{\circ}\text{C}$ or $>2000^{\circ}\text{F}$) Combustion Processes

Increasing concern regarding the leaching of heavy metals from biosolids ash has led to the development of several combustion systems wherein the biosolids ash is heated beyond the point of fusion. Then, a glassy slag is formed. Leaching tests on the slag show essentially no solvation of metals. Several companies have plants, and plants based on this operating concept are in planning for use in Japan, where limited land area focuses great value on the minimization of ultimate residue (ash) disposal. The Kubota Company, drawing on Woetzhke furnace designs developed in the 1960s in West Germany, offers one such design.

The primary furnace used by Kubota is a slowly rotating, refractory lined cylindrical chamber with an outlet tap in the center (Figure 10.25). The chamber has a relatively flat, refractory-lined, fixed, reverse-conical roof equipped with down-firing burners. There is a clearance (the annulus between the roof and lower chamber) through which a stream of predried biosolids is moved by the rotation of the lower body into the cavity between the roof and the lower chamber. There, the burners, augmented with preheated air, reduce the biosolids to a molten slag. The combustion heat contained in the biosolids solids is released by furnishing excess air through the burner ports. The size of the cavity may be adjusted to increase (larger cavity) or decrease (smaller cavity) the processing rate.

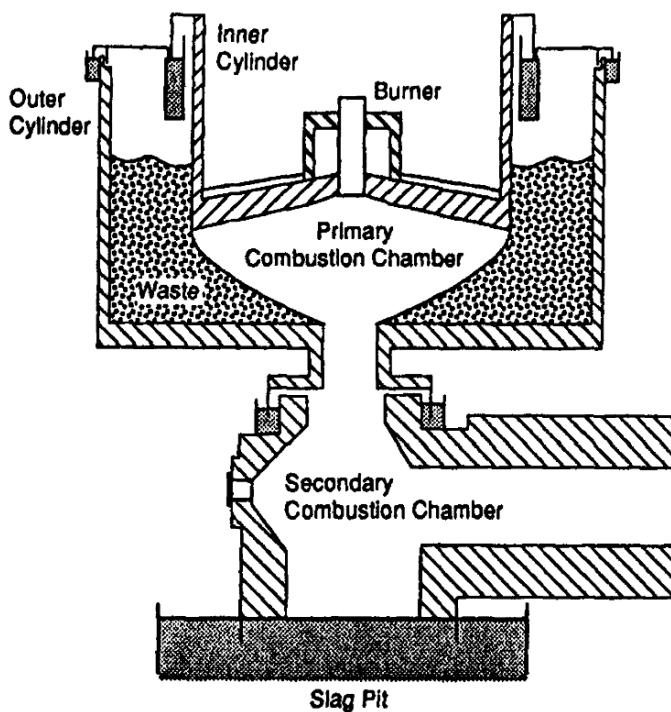


Fig. 10.25. Kubota melting furnace.

The primary furnace cavity is maintained slightly sub-stoichiometric. This produces both maximum temperatures and minimizes the gas flow in order to minimize entrainment.

The molten slag and off-gas from the primary chamber flow down through a water-cooled “monkey” discharge opening into a secondary combustion chamber. The slag continues to fall to a solidification area or directly into a water quench. Slow cooling favors crystal growth and forms a dense, strong, obsidian-like black glass. Faster cooling results in a granular black fractured glass with poorer structural characteristics than the slow-cooled product.

Addition of secondary air completes the combustion in a tunnel-type afterburner. The hot gases from the secondary are used to preheat the combustion air for the primary furnace (using a heat exchanger similar to the hot windbox fluid bed) and then are tempered and used to dry the incoming biosolids. Off-gas from the dryer is cleansed with an electrostatic precipitator, condenser, and scrubber. The use of fossil fuel is limited by the low overall air quantity supplied to the unit (10% to 30% excess). The temperature in the primary furnace is maintained at approximately 1450°C for most biosolids to yield acceptable biosolids fluidity. The furnace operation is stable as seen from strip charts of temperature and gas composition.

The operation of the primary chamber sub-stoichiometric greatly limits the formation of fuel-nitrogen NO_x . Net NO_x in the flue gases from several plants averaged 100 to 150 ppm. Although one might expect the high primary furnace temperatures to result in emission of heavy metals, data from the manufacturer indicate that the majority of the metals are bound into the fluid slag that blankets the incoming biosolids and do not show up as heightened metal emissions.

The key environmental characteristic of the Kubota furnace is the ash, which exhibits essentially no leaching (below the detection limit by atomic absorption for cadmium, chromium +6 and +3, arsenic, mercury, and lead. There was also no detection of PCBs or cyanide ion, although these species appear in the raw biosolids. The slag formed has a specific gravity of from 2.4 to 2.7 and appears useful as a clean fill or road-bed material.

The primary benefits of the Kubota furnace relate to the potential to have no net waste for disposal (assuming that the excellent leaching characteristics and strength characteristics of the glassy ash make it disposable as a fill or usable as an aggregate with cement in patio blocks or other items of commerce rather than a waste). Fuel requirements are modest, but the plant has a high capital cost. Operations are complex including dryers, several air cleansing systems, and a mechanically sophisticated, high-temperature furnace and heat-recovery system.

Data indicate that acceptable long-term operation is possible. Three or more plants are now operating in Japan using the Kubota melting process, with the earliest plant coming on-line in 1975. The system must be considered to be in an advanced state of development.

4.6. Discussion

There are many alternatives open to the biosolids management professional for the processing of wastewater biosolids using thermal methods. These processes range from simple and mechanically complex drying systems to high-temperature slagging furnaces. The environmental implications of these plants are generally controllable and focus on

air emissions (including odor). Although the capital costs are intensive and often there is the burden of continuing high operating expense, the significant reduction in weight or volume effected by these processing methods is increasingly justified by spiraling hauling and dumping fees.

The selection of a biosolids management system requires many factors (technical, economic, political, etc.) to be weighed and balanced. These decisions are rightly the responsibility of the ultimate owner or operator of the system. Often, cost factors dominate in the selection decision. Capital and operating and maintenance costs are basic and important criteria. In comparing alternatives, however, one must be sure that the capital cost estimate includes all elements (spare parts, provision for extra-rugged construction and materials of construction, etc.) that adequately protect continued operability and on-line availability. Operating cost estimates should include consideration of training expenses, higher than normal operator wage scales (to ensure a sophistication of operator compatible with sophisticated equipment and other reasonable and prudent contributions to keeping the costly and critical equipment operating at peak. Finally, maintenance cost should include the special elements that recognize the more sophisticated and maintenance-prone working environment of high-temperature incineration systems. These include contract maintenance of instrumentation and control systems, regular refractory replacement and repair, and so forth. Flexibility and expandability are important criteria for wastewater systems with changing processes, dewatering methods or polymers, growth of the system, etc., which may result in a continuously changing operating mode for the system.

Environmental impact must be evaluated in depth and carefully considered. Often, a risk assessment type document must be prepared as part of that evaluation. Also, community and regulatory perspectives change; the high capitalization systems used for most thermal processing alternatives cannot be readily modified to adapt. Fit with the community labor forces and willingness to spend are particularly important for small communities where sophisticated, high-cost systems, however appealing, may be inappropriate selections in view of competition with high-tech industry (with higher wages and benefits) for high-quality operators; the imperative for high-quality maintenance and associated costs for thermal systems; and other factors reflecting problematical local conditions. It should be said, however, that I have seen many small communities with excellent records in the operation of very costly and sophisticated sludge management systems.

5. ECONOMICS OF INCINERATION

Incineration is often the highest-cost approach to waste management. Consequently, an understanding of the economics of incineration is an important part of engineering and management decision making. Unfortunately, providing definitive guides to economic analysis is as difficult as it is for design.

The costs of incineration have increased rapidly since the 1970s. The reasons underlying the cost increases parallel those that have gripped the overall U.S. economy during this period: rising interest rates, equipment and construction costs, and labor and energy rates. Beyond these background inflationary factors, the increasing equipment

Table 10.24
Elements of capital costs for incineration systems

I. Incineration system
A. Waste conveyance
1. Open or compaction vehicles, commercial containers
2. Special design containers
3. Piping, ducting, conveyors
B. Waste storage and handling at incinerator
1. Waste receipt and weighing
2. Pit and crane, floor dump and front-end loader
3. Holding tanks, pumps, piping
C. Incinerator
1. Outer shell
2. Refractory
3. Incinerator internals (grates, catalyst)
4. Burners
5. Fans and ducting (forced and induced draft)
6. Flue gas conditioning (water systems, boiler systems)
7. Air pollution control and continuous emission monitoring (CEMs)
8. Stacks and flues
9. Residue handling
10. Automatic control and indicating instrumentation
11. Worker sanitary, locker, and office space
II. Auxiliary systems
A. Land preparation, grading, clearing and grubbing, etc.
B. Buildings, roadways, parking areas
C. Foundations
D. Special maintenance facilities
E. Steam, electrical, water, fuel, and compressed air supply
F. Secondary pollution control
1. Residue disposal (landfill, etc.)
2. Scrubber wastewater treatment
III. Nonequipment expenses
A. Engineering fees
B. Land costs
C. Permits
D. Interest during construction
E. Spare parts inventory (working capital)
F. Investments in operator training
G. Start-up expenses (engineering, testing, laboratories, etc.)
H. Technology fees to engineers, vendors

investment associated with the sophisticated air pollution control systems required by toughening emission codes and the investment involved in the generation of electrical power (turbines, condensers, cooling towers, switchgear, etc.) add capital expense and increase the needed skills and thus cost of the labor force. For refractory incinerators and

Table 10.25
Elements of operating cost for incineration
systems

I. Fixed costs (credits)
A. Repayment of debt capital
B. Payment of interest on outstanding capital
C. Tax credits for depreciation
II. Semivariable costs
A. Labor (including supervision) with overhead
B. Insurance
D. Operating supplies
D. Maintenance and maintenance supplies
III. Variable costs (credits)
A. Steam usage (or credits)
B. Electricity usage (or credits)
C. Water supply and sewerage fees
D. Oil or natural gas fuels
E. Compressed air
F. Chemicals (catalysts, water treatment)
G. By-product credits
H. Disposal fees

particularly for upgraded older units where operation at high excess-air levels yielded large flue-gas flow rates, the requirement for sophisticated air-pollution control systems was a major factor leading to shutdown.

5.1. General

It would be a gross simplification, in most cases, to suggest that incineration system capital costs could be reduced to a simple table or nomograph. Usually, the designs are highly customized, reflecting unique waste handling, ducting, local regulatory requirements, degree of automatic control, enclosure aesthetics, etc., which greatly affect the final system cost, even if the basic incinerator itself is of predictable cost. Similarly, operating costs reflect staffing practices, localized labor and utility costs, localized unit values for byproduct materials or energy, etc. Further, the bonded capital investment borne by the host community (assuming a design, build, and operate [DBO] facility development by a system vendor) depends importantly on the facility profit objectives of the vendor. In many cases, the vendor sees the long-term waste disposal service as the primary money-maker, and the construction carries only a nominal profit margin. Others seek a substantial profit “up front” on the capital investment as well as the longer term tipping fee income stream that is collected over the operating life of the service contract.

Consequently, the following subsections emphasize the elements of cost analysis as applied to incineration rather than simplified general numbers. The experienced engineer will recognize this not as an evasion but rather as an explicit recognition of the dangers of oversimplification.

Table 10.26

Solid waste weight percent characterization data (1988, 1990) (58)

Waste category	Indianapolis, IN	Kauai, HI	King Co., WA	Bergen Co., NJ	Monroe Co., NY	Ann Arbor, MI	Portland, OR	San Diego, CA	Santa Cruz, Co., CA	National Estimate
Paper	38	26	27	44	42	29	29	26	33	34
Plastics	8	7	7	9	10	8	7	7	8	9
Yard debris	13	20	19	9	7	8	11	21	15	20
Misc. organics	22	24	31	17	24	39	33	23	18	20
Glass	7	5	4	7	10	4	3	4	7	7
Aluminum	1	1	1	1	1	1	1	1	1	1
Ferrous metal	4	6	3	5	5	5	7	3	5	7
Nonferrous metal	0	1	1	4	0	2	0	0	0	0
Misc. Inorganics	0	3	7	5	0	2	9	6	6	2
Other	0	9	0	3	0	2	1	10	7	0

Co., county.

Table 10.27
Estimated average percent moisture in refuse on
an “as-discarded” and “as-fired” basis (59)

Component	As-fired (typical)	As-discarded
Food wastes	63.6	70.0
Yard wastes	37.9	55.3
Miscellaneous	3.0	2.0
Glass	3.0	2.0
Metal	6.6	2.0
Paper	24.3	8.0
Plastics	13.8	2.0
Leather and rubber	13.8	2.0
Textiles	23.8	10.0
Wood	15.4	15.0

5.2. Capital Investment

For many prospective incinerator owners, the initial capital investment is the crucial issue. This is particularly true for industry, where the return on invested capital is often the prime measure of business performance. Table 10.24 shows the major capital expenditures. Note also that both purchased equipment and installation cost (the latter can be over 200% of the equipment cost alone) should be evaluated.

5.3. Operating Costs

Although capital investment is an important aspect, the actual *total unit cost*, allowing for the cost of capital, but including all operating costs, is a more incisive measure of economic impact. For example, contract hauling, typically, requires little or no investment by the owner, but may represent an unacceptably high unit cost for disposal or a long-term liability of considerable worth. Similarly, high-energy scrubbers are lower in capital cost than electrostatic precipitators, but at equivalent efficiency consume so much power that their cost per unit of gas cleaned is much higher. Typical elements of operating cost for incineration systems are shown in Table 10.25.

6. AN APPROACH TO DESIGN

How then do you design an incinerator? I wish the answer were straightforward, with the underlying principles uncluttered with contradiction and free of the need to apply both technical and value judgments. This section, however, can only scratch the surface of the challenge of system design; we will attempt generally to structure, if not guide in detail, the design process.

6.1. Characterize the Waste

Obtain the best practical characterization of the quantity and composition of the waste. Keep in mind future growth and the impact of seasonality and changes in technology and economics on operational patterns and decision making.

Table 10.28
Estimated final analysis of refuse categories, percent, dry basis

Category	C	H	O	N	Ash	S	Fe	Al	Cu	Zn	Pb	Sn	P*	Cl	Se	Fixed carbon
Metal	4.5	0.6	4.3	0.05	90.5	0.01	77.3	20.1	2.0	-	0.02	0.6	0.03	-	-	0.5
Paper	45.4	88	42.1	0.3	6.0	0.12	-	-	-	-	-	-	-	-	Trace	11.3
Plastics	59.8	8.3	19.0	1.0	11.6	0.3	-	-	-	-	-	-	0.01	6.0	-	5.1
Leather/rubber	59.8	8.3	19.0	1.0	11.6	0.3	-	-	-	2.0	-	-	-	-	-	6.4
Textiles	46.2	6.4	41.8	2.2	3.2	0.2	-	-	-	-	-	-	0.03	-	-	3.9
Wood	48.3	6.0	42.4	0.3	2.9	0.11	-	-	-	-	-	-	0.05	-	-	14.1
Food waste	41.7	5.8	27.6	2.8	21.9	0.25	-	-	-	-	-	-	0.24	-	-	5.3
Yard waste	49.2	6.5	36.1	2.9	5.0	0.35	-	-	-	-	-	-	0.04	-	-	19.3
Glass	0.52	0.07	0.36	0.36	99.0	-	-	-	-	-	-	-	-	-	-	0.4
Misc.	13.0 ^a	2.0 ^a	12.0 ^a	12.0 ^a	70.0	-	-	-	-	-	-	-	-	-	-	7.5

* Estimated (varies widely), excludes phosphorus in CaPO₄.

^a From ref. 7.

Table 10.29
Ultimate analysis of annul average 1970 mixed municipal refuse

Category	Wt%		Moisture as discarded	Composition of average refuse, kg/100 kg dry solids						Total Wt, kg
	As fired	As discarded		Ash	C	H ₂	O ₂	S	N ₂	
Metal	8.7	8.2	2.0	10.13	0.50	0.067	0.481	0.0011	0.0056	11.19
Paper	44.2	35.6	8.0	2.74	20.70	2.781	19.193	0.0547	0.1368	45.59
Plastics	1.2	1.1	2.0	0.17	0.90	0.125	0.285	0.0045	0.0150	1.50
Leather and rubber	1.7	1.5	2.0	0.24	1.23	0.170	0.390	0.0062	0.0205	2.05
Textiles	2.3	1.9	10.0	0.08	1.10	0.152	0.995	0.0048	0.0523	2.38
Wood	2.5	2.5	15.0	0.09	1.43	0.178	1.260	0.0033	0.0089	2.96
Food waste	16.6	23.7	70.0	2.17	4.13	0.574	2.730	0.0248	0.2772	9.90
Yard waste	12.6	15.5	50.0	0.54	5.31	0.701	3.890	0.0378	0.3129	10.79
Glass	8.5	8.3	2.0	11.21	0.06	0.008	0.041	—	0.0034	11.32
Miscellaneous	1.7	1.7	2.0	1.62	0.30	0.046	0.278	—	0.0696	2.32
	100.0	100.0		28.99	35.66	4.802	29.543	0.1372	0.9022	100.00

From ref. 7.

Table 10.30
Average refuse summary, as-fired basis: 100-kg average refuse

Component	Weight percent (dry basis)	Weight percent (wet basis)	Mols (wet basis)
Moisture (H ₂ O)	—	28.16	1.564
Carbon, C	35.66	25.62	2.135
Hydrogen, H ₂ = bound	3.69	2.65	1.326
Oxygen, O = bound	29.52	21.21	1.326
Hydrogen, H ₂	1.11	0.80	0.399
Sulfur, S	0.1372	0.10	0.003
Nitrogen, N ₂	0.0396	0.64	0.023
Ash	28.99	20.82	—
Total	100.00	100.00	6.770

From ref. 59.

6.2. Lay Out the System in Blocks

Too often, incineration facilities are developed in pieces, with insufficient attention being given to the mating of interfaces between various elements. Remember the concept of system.

6.3. Establish Performance Objectives

Review present and prospective regulatory requirements. Evaluate the needs for volume reduction, residue burnout, or detoxification. Apply these to appropriate points in the facility layout.

6.4. Develop Heat and Material Balances

Using the techniques developed early in this chapter, determine the flows of material and energy in the waste, combustion air, and flue gases. Take into consideration probable materials of construction and establish reasonable limits on temperatures. Explore the impact of variations from the average waste feed composition and quantity. In practice, these off-average characteristics generally better characterize the day-to-day operating conditions.

6.5. Develop Incinerator Envelope

Using heat release rates per unit area and per unit volume, the overall size of the system can be established. Using burning rate, flame length and shape, kinetic expressions, and other analysis tools (1), establish the basic incinerator envelope. The final shape depends on judgment, as well as on these calculations. Draw on the literature and the personal experience of others. Interact with other engineers, vendors, operators, and designers of other combustion systems with similar operating goals or physical arrangements. Attempt to find the balance between being overly conservative at high cost and the unfortunate fact that few of the answers are tractable to definitive analysis

Table 10.31
Ultimate analyses and heating value of waste components

Waste component	Weight %, dry						HHV, kcal/kg	
	C	H	O	N	S	Noncombustible	As received	Dry
Paper and paper products								
Paper, mixed	43.41	5.82	44.32	0.25	0.20	6.00	3778	4207
Newsprint	49.14	6.10	43.03	0.05	0.16	1.52	4430	4711
Brown paper	44.90	6.08	47.34	0.00	0.11	1.07	4031	4281
Trade magazines	32.91	4.95	38.55	0.07	0.09	23.43	2919	3044
Corrugated boxes	43.73	5.70	44.93	0.09	0.21	5.34	3913	4127
Plastic-coated paper	45.30	6.17	45.50	0.18	0.08	2.77	4078	4279
Paper food cartons	44.74	6.10	41.92	0.15	0.16	6.93	4032	4294
Food and food waste								
Vegetable food waste	49.06	6.62	37.55	1.68	0.20	4.89	997	4594
Fried fats	73.14	11.54	14.82	0.43	0.07	0.00	9148	9148
Mixed garbage I	44.99	6.43	28.76	3.30	0.52	16.00	1317	4713
Mixed garbage II	41.72	5.75	27.62	2.97	0.25	21.87	—	4026
Trees, wood, brush, plants								
Green logs	50.12	6.40	42.26	0.14	0.08	1.00	1168	2336
Demolition softwood	51.0	6.2	41.8	0.1	<0.1	0.8	4056	4398
Waste hardwood	49.4	6.1	43.7	0.1	<0.1	0.6	3572	4056
Lawn grass	46.18	5.96	36.43	4.46	0.42	6.55	1143	4618
Ripe leaves	52.15	6.11	30.34	6.99	0.16	4.25	4436	4927
Wood and bark	50.46	5.97	42.37	0.15	0.05	1.00	3833	4785
Brush	42.52	5.90	41.20	2.00	0.05	8.33	2636	4389
Grass, dirt, leaves	36.20	4.75	26.61	2.10	0.26	30.08	—	3491
Domestic wastes								
Upholstery	47.1	6.1	43.6	0.3	0.1	2.8	3867	4155
Tires	79.1	6.8	5.9	0.1	1.5	6.6	7667	7726
Leather	60.00	8.00	11.50	10.00	0.40	10.10	4422	4917
Leather shoes	42.01	5.32	22.83	5.98	1.00	22.86	4024	4348
Rubber	77.65	10.35	—	—	2.00	10.00	6222	6294
Mixed plastics	66.00	7.20	22.60	—	—	10.20	7833	7982
Polyethylene	84.54	14.18	0.00	0.06	0.03	1.19	10,932	10,961
Polystyrene	87.10	8.45	3.96	0.21	0.02	0.45	9122	9139
Polyvinyl chloride	45.14	5.61	1.56	0.08	0.14	2.06*	5419	5431
Linoleum	48.06	5.34	18.70	0.10	0.40	27.40	4528	4617
Rags	55.00	6.60	31.20	4.12	0.13	2.45	3833	4251
Municipal wastes								
Street sweepings	34.70	4.76	35.20	0.14	0.20	25.00	2667	3333

* Remaining 45.41% is chlorine.
 From ref. 2.

Table 10.32
Range of total metal concentration in various ash types—mg/kg (18)

Ash type	No. samples	Cadmium	Copper	Lead	Zinc
Bottom ash					
Grate	4	<1.0–48.2	420–12,600	300–2750	903–2420
Siftings	60	<0.68–67.6	122–21,200	738–103,000	412–46,100
Fly ash					
Boiler tube	7	130–389	534–988	4280–16,100	11,100–24,300
Spray dryer	5	38.0–59.4	312–880	1060–1710	2830–9630
Bag house	56	40–578	142–4,399	1100–10,340	280–92,356
Combined	54	7.7–120	445–17,355	561–5,100	733–53,800

and computation. Particularly, talk to operators of systems. Too often the designers speak only to one another, and the valuable insights of direct personal experience go unheard and, worse, unasked for.

6.6. Evaluate Incinerator Dynamics

Apply the jet evaluation methodology, buoyancy calculations, empirical relationships, and conventional furnace draft and pressure drop evaluation tools to grasp, however inadequately, the dynamics of the system.

6.7. Develop the Design of Auxiliary Equipment

Determine the sizes and requirements of burners, fans, grates, materials-handling systems, pumps, air compressors, air pollution control systems, and the many other auxiliary types of equipment comprising the system. Here, again, the caution is to be generous, protective, and rugged. The cardinal rule is to prepare for *when* “it” happens, not to argue about *whether* “it” will happen.

6.8. Review Heat and Material Balances

This self-explanatory step helps to reinforce the systems perspective by tracking the flows through one after another component part.

6.9. Build and Operate

In many cases, fortunately, nature is kind; reasonable engineering designs will function, though perhaps not to expectations or with maintenance expense or equipment availability different from what might be wished. At times, plants built using the most detailed analysis and care result in failure. Such is the lot of workers in the complex but fascinating field of combustion and incineration.

APPENDIX: WASTE THERMOCHEMICAL DATA

The chemical composition and heat of combustion of waste materials is a matter of concern to the design engineer, to the operator of an incinerator, and to the engineer involved in incinerator troubleshooting.

Waste composition and heat content affect combustion air requirements, flame temperatures, and bed burning processes, and impact on corrosion, air pollution, and other important incinerator operating characteristics. Ideally, refuse composition is determined empirically in a comprehensive and scientifically planned and executed program of waste sampling and analysis. Often, however, an engineer requires compositional data for use in preliminary studies. In such cases, data are needed that might be called typical or average. The data presented below may serve this need. A guideline, however, is offered: There is no typical municipal refuse. Indeed, I recommend that the word *average* be redefined, as follows: *average* is the value assigned to an often critical design parameter that is *never* observed in practice. While tongue-in-cheek, this redefinition is intended to encourage the analyst to extensively use “what-if” calculation methods to assess possible system requirements and needs.

A more comprehensive assembly of data on the properties and generation rates of municipal refuse and other wastes is available elsewhere (1, 2).

A.1. Refuse Composition

The seasonal and annual average compositions shown in Table 10.26 were derived from an analysis of data sets from municipalities throughout the U.S. (59). These data illustrate the wide variation to be expected in waste sampling. In addition to these regional differences, one can expect seasonal variation in the composition and quantity of wastes. The average of 3 years of data from New Jersey (58) from a region where the waste was about 54% residential and 46% commercial and industrial showed 122% of the annual average volumetric monthly waste quantity was received in May; about the average from July through October; and then an almost linear decline to only 78% of the average in February, climbing back to the peak in May. The refuse density varied from 435 kg/m³ in the summer to 385 kg/m³ in the winter.

In reviewing waste composition data as input to engineering calculations, it is necessary to take account of the fact that waste materials often exchange moisture when they are mixed in the waste storage container. As an example, consider a sheet of newspaper with a typical moisture regain (the equilibrium moisture content achieved by exchange between the dry material and the normally humid atmosphere) corresponding to about 8% moisture. Wrapping the garbage from dinner (typically 60% to 70% moisture) makes the paper wet and dries the food material. Therefore, when one takes a sample of this mixed waste and weighs the newspaper fraction, the number of pounds in the “paper category” is higher than that which corresponds to the “standard” moisture 8% content, making it appear as though there is more “standard paper” in the waste than is really there. If, then, we take the chemical composition (percent carbon, hydrogen, etc.) and reference heat content of standard paper times its “weight” in the sample, we will calculate an incorrect air requirement and an incorrect heat release potential.

Consequently, when analyzing waste composition data, the results are more useful if the moisture levels of the components are adjusted, category by category from the moisture content found after moisture exchange (the “as-fired” basis), to a moisture content corresponding to the manufactured state of the materials (the “as-discarded” basis). The as-discarded basis is useful in indicating the true relative magnitude of waste generation for the various categories, as the appropriate basis for estimating salvage

potential, and as the basis for forecasting refuse generation rates and chemical and physical properties for combustion calculations. Such basis adjustments can become critical for wastes where a substantial fraction of the waste is very moist and thus where profound effects of moisture transfer occur. (6, 8)

The moisture content values shown in Table 10.27 can be used to effect this basis shift. Note that it is generally necessary for the analyst to adjust the assumptions for the “as-fired” state such that the average total moisture percentage in the mixed waste is unchanged by the recalculation of the percentage composition. Spreadsheet models to facilitate such adjustments in composition are available elsewhere (1).

A.2. Solid Waste Properties

The categorical composition is the starting point for the development of parameters of interest to the incinerator designer. Although the manipulation of gross categorical data to establish average chemical composition, heat content, and the like requires assumptions of questionable accuracy, it is a necessary compromise. Typically, between 1 and 3 tons of waste from a waste flow of 200 to 1000 ton/d are analyzed to produce a categorical composition. Then a still smaller sample is hammer-milled and mixed, and a 500-mg sample is taken. Clearly, a calorific value determination on this sample is, at best, a rough reflection of the energy content of the original waste.

A.2.1. Thermochemical Analysis

Stepping from the categorical analysis to a mean thermochemical analysis provides the basis for stoichiometric calculations and energy balances:

- Mixed municipal refuse: Chemical data for average municipal refuse components and for the mixed refuse shown in Table 10.26 are presented in Tables 10.28 to 10.30. These data were developed with the typical refuse of 1970 in mind, but should be applicable to almost any First World waste material.
- Specific waste components: Data for specific waste components are given in Table 10.31. These data may be used when detailed categorical analyses are available or to explore the impact of refuse compositional changes. Once a weight-basis generation rate is established, data on the heating value of waste components are of great interest to the combustion engineer. Note that the “As received” column corresponds to the “As discarded” moisture category described above, a point that emphasizes the importance of considering the moisture transfer process between waste components in developing compositions and heating values for engineering analysis.

A.3. Ash Composition

Table 10.32 shows the range of total metal concentration found in mass burn MWC systems.

NOMENCLATURE

c , u = concentration or velocity in a jet (g mol/L, m/s)

c_m , u_m = concentration or velocity on the centerline of a jet (g mol/L, m/s)

c_0 , u_0 = concentration or velocity in the nozzle fluid of a jet (g mol/L, m/s)

d_0 = initial diameter of carbon particle or nozzle diameter (m, ft)

- f_a, f_b = mol fraction of component a, b
 g_c = acceleration due to gravity (ft/s^{-2})
 HHV = higher heating value (kcal/kg , BTU/lb , kcal/kg mol , BTU/lb mol)
 k_d = diffusion rate constant for carbon consumption reaction
 K_p = equilibrium constant
 k_s = kinetic rate constant for carbon consumption reaction
 M = cross-flow parameter (see Equation 29)
 Mc_p^0 = mean specific heat at zero pressure
 $Mc_{p\text{avg}}^0$ = average specific heat at zero pressure between two temperatures
 \dot{m}_0 = integrated total jet flow at the nozzle (kg/sec)
 \dot{m}_x = integrated total jet flow at a distance x (kg/sec)
 N = number of mols (gram mols, kilogram mols, pound mols)
 Nf_0 = NO concentration for 100% conversion of fuel nitrogen (N_f) to NO
 N_{Re} = Reynolds number (dimensionless)
 P = pressure (atm, Kpa, psi, etc.)
 P_A, P_B = partial pressure of component A, B, etc
 $PM_{2.5}$ = particulate matter with diameter less than $2.5 \mu\text{m}$
 Q = rate of carbon consumption ($\text{g/cm}^{-2} \text{s}^{-1}$)
 R = jet radius (m)
 R, R' = universal gas constant (see Table 10.1)
 S = mean residence time (sec)
 T = temperature ($^{\circ}\text{C}$, $^{\circ}\text{F}$, $^{\circ}\text{K}$, $^{\circ}\text{R}$)
 T = time (s)
 t_b = burning time of carbon particle
 T_0 = temperature at reference condition ($^{\circ}\text{C}$, $^{\circ}\text{F}$, $^{\circ}\text{K}$, $^{\circ}\text{R}$)
 V = volume (m^3 , ft^3)
 V = velocity
 W = emission factor of particulate matter (kg/ton)
 X = downstream distance in jet analysis (m)
 Y = fraction of fuel nitrogen converted to NO_x
 Y = distance perpendicular to the axis of a jet (m)
 y_0 = generalized elevation above a reference (m)
 Δh = enthalpy change (kcal , BTU)
 μ_0 = viscosity ($\text{kg m}^{-1}\text{sec}^{-1}$)
 ρ = density (kg/m^3 , lb/ft^3)
 ρ_a = density of ambient fluid (kg/m^3 , lb/ft^3)
 ρ_0 = density of nozzle fluid or initial value (kg/m^3 , lb/ft^3)

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